PULSED POWER SYSTEM
脈衝功率系統

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2023 Fall Semester

Tuesday 9:10-12:00

Lecture 12

http://capst.ncku.edu.tw/PGS/index.php/teaching/

Online courses:

https://nckucc.webex.com/nckucc/j.php?MTID=md577c3633c5970f80cbc9e821927e016

2023/12/5 updated

Grading

- ~~Weekly presentations – 30 %~~
  - ~~Class review.~~

→ Homework – 30 %

- Final presentations – 70 %
  - Design of a pulsed-power system – 35 %.
  - Applications of pulsed-power system – 35 %.

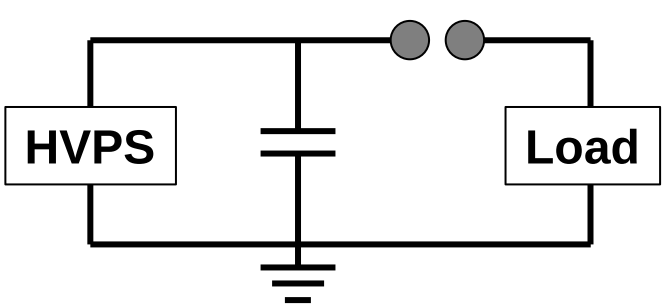
- **Final presentation on 12/26.**

Outlines

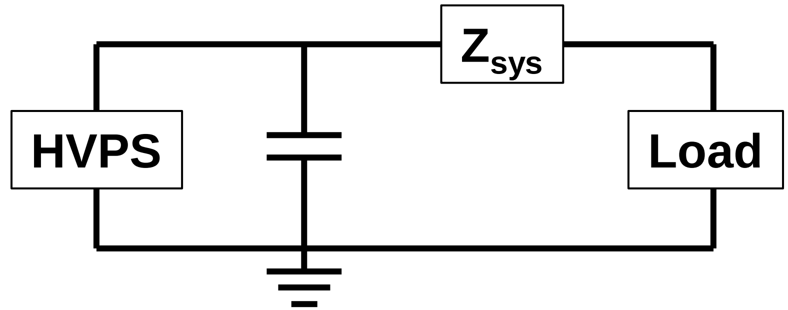
- Switches
  - Closing switches: the switching process is associated with voltage breakdown across an initially insulant element.
  - Opening switches: the switching process is associated with a sudden growth of its impedance.
- **Pulse-forming lines**
  - Blumlein line
  - **Pulse-forming network**
  - Pulse compressor
- Pulse transmission and transformation

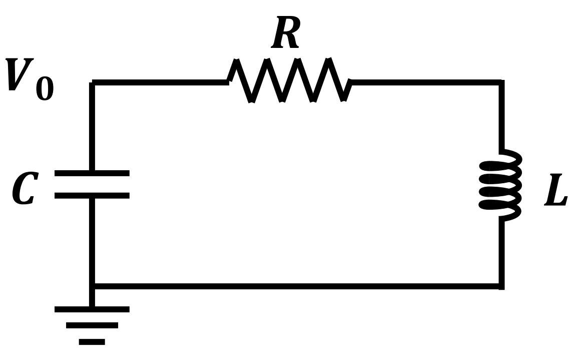
A simple pulsed-power system is a RLC circuit

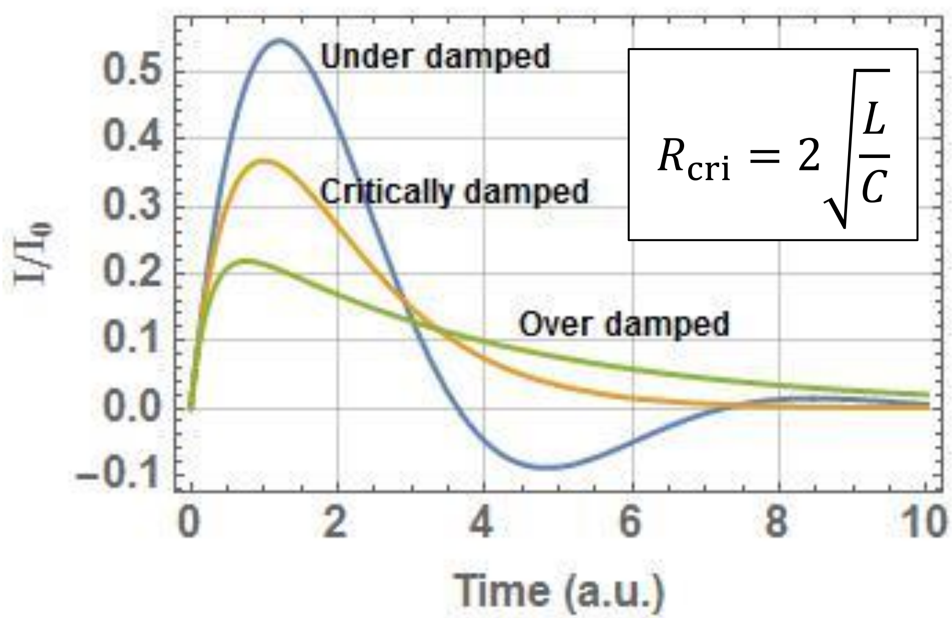
- **Before discharge**



- **After discharge**

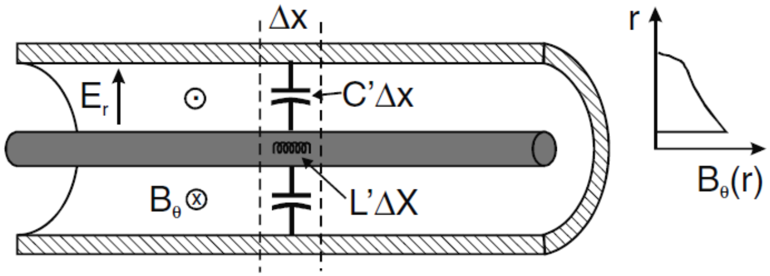


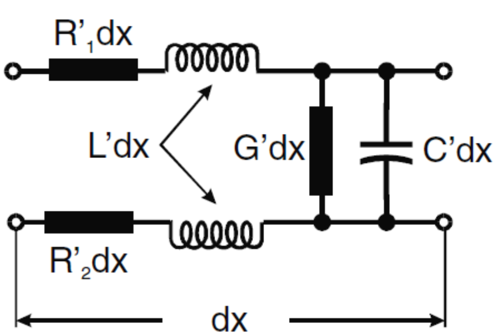


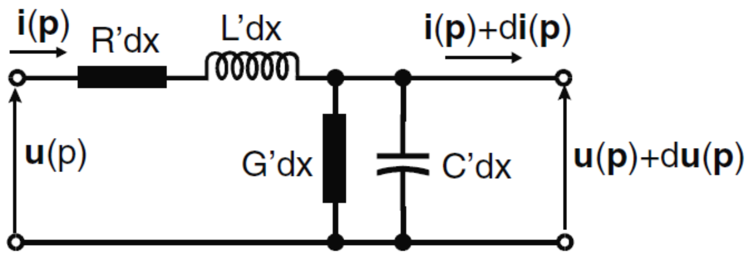


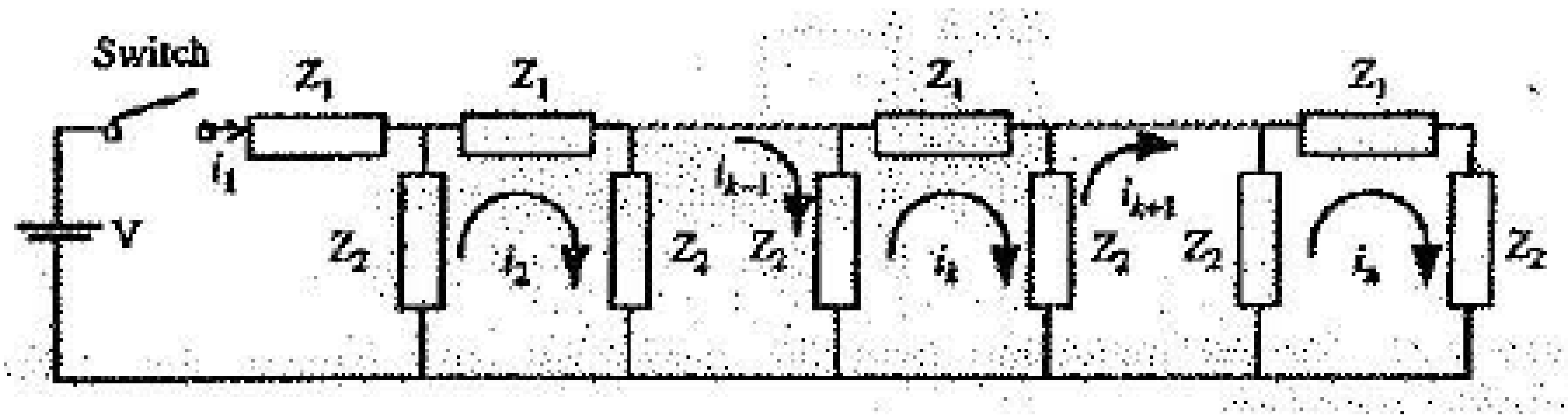
- **How can we generate a square current pulse?**

Pulse-forming network (PFN)

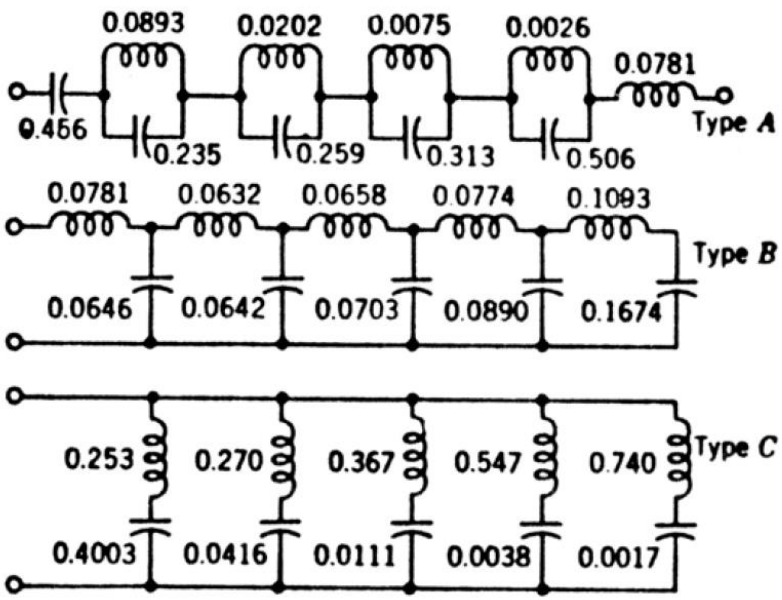


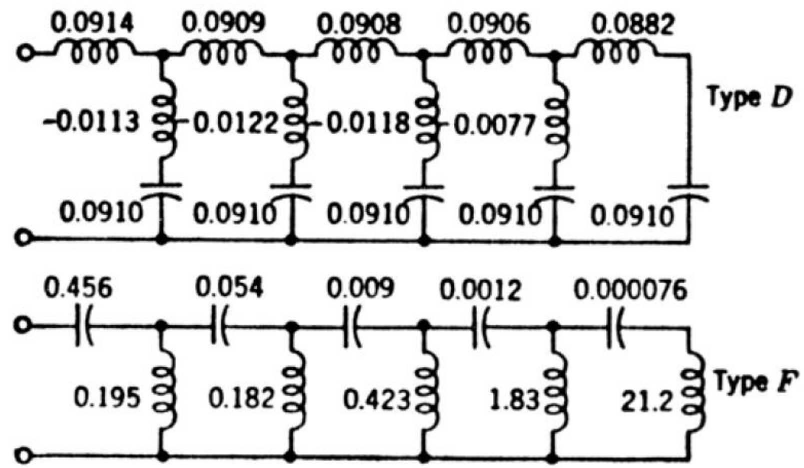






Equivalent Guillemin Networks





Pule-forming LC chain

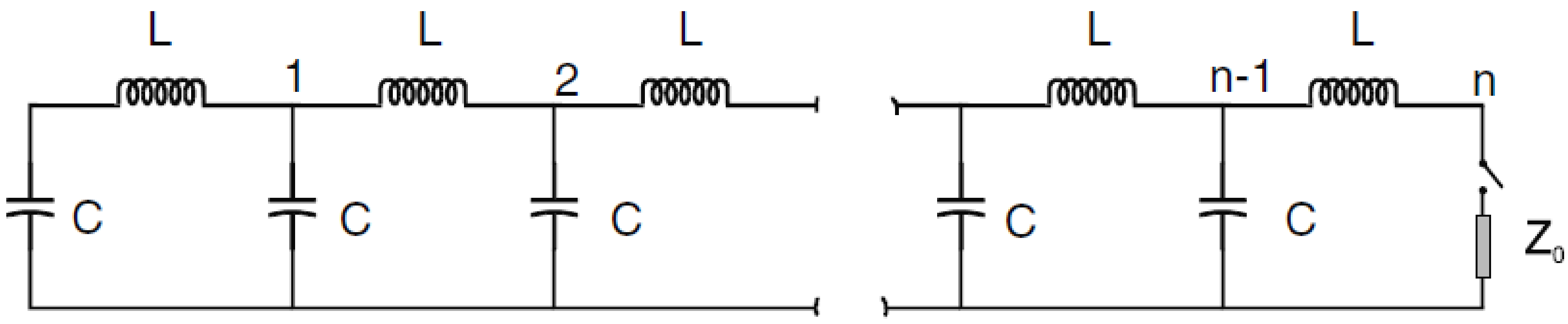
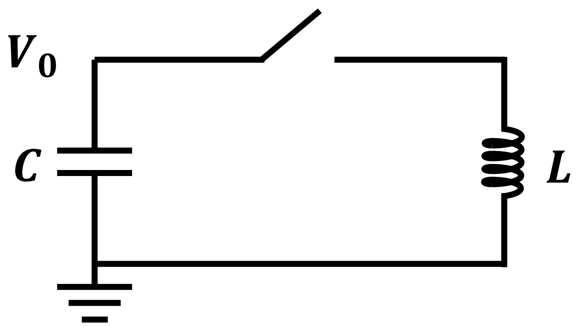


Fig. 5.11. Pulse-forming *LC* chain

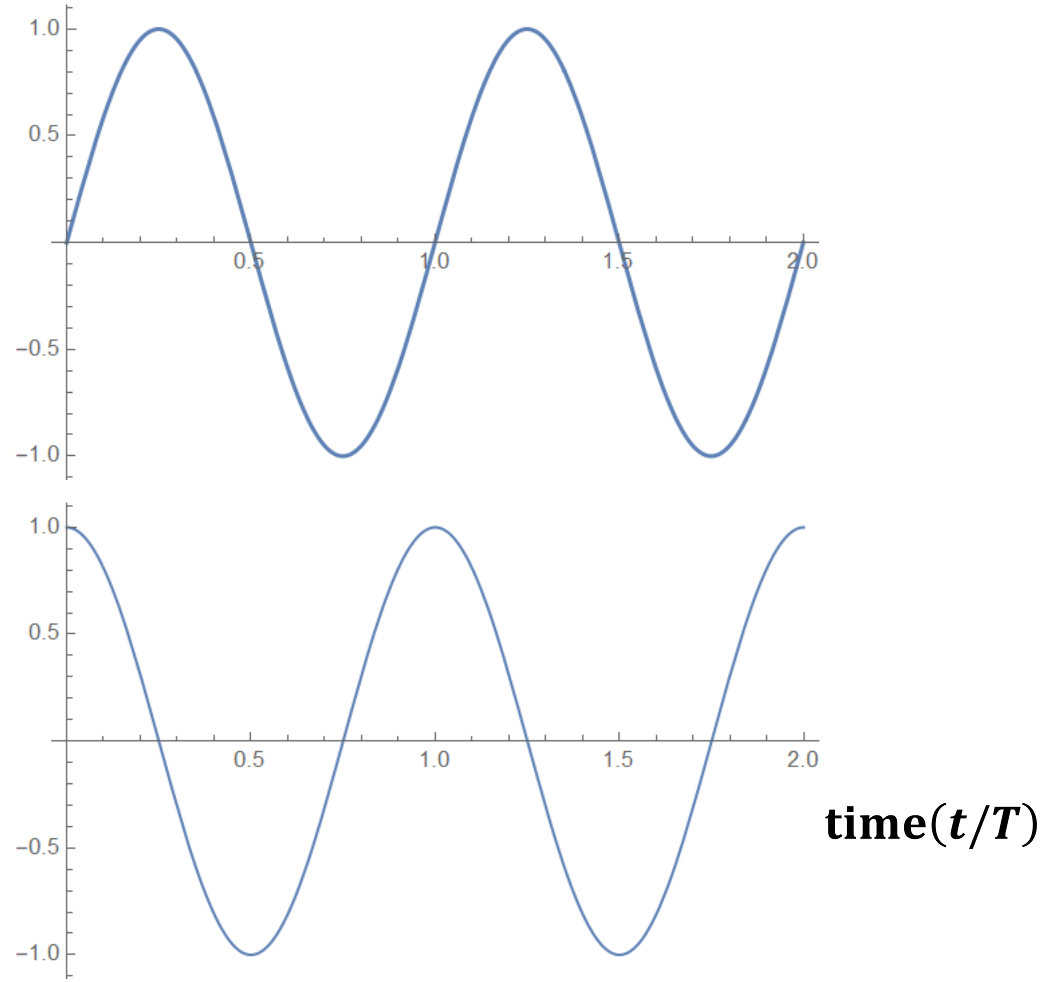
The current output of a LC circuit is a basis of Fourier series



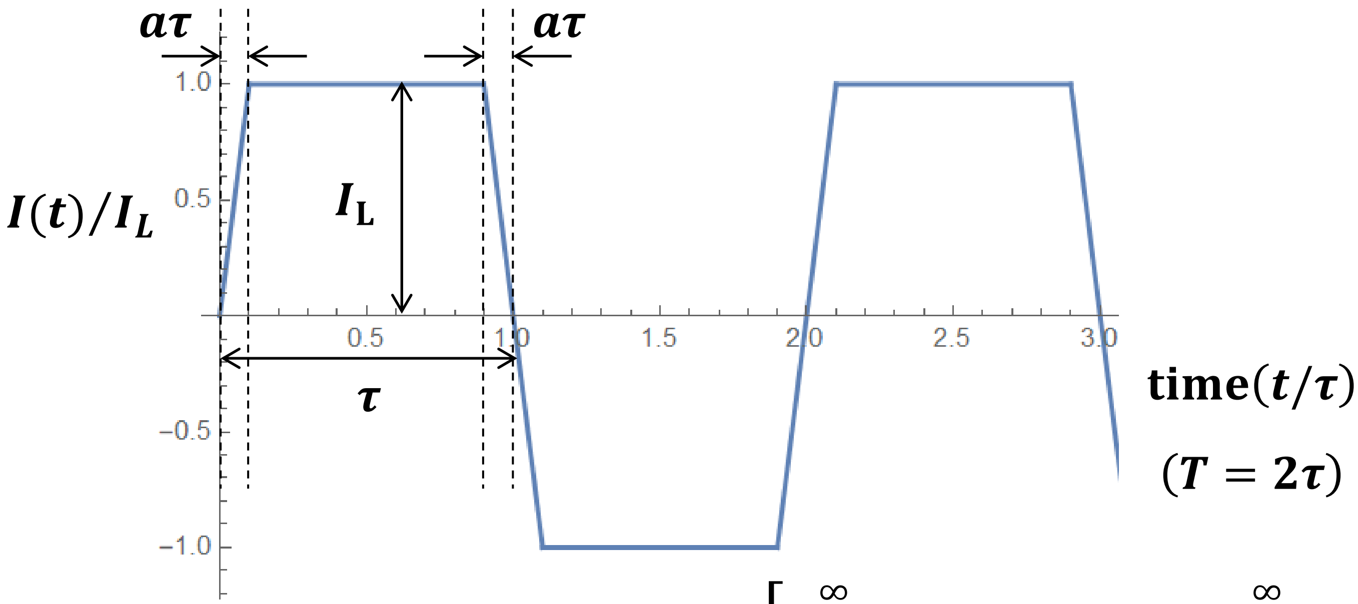
$$I(t) = V_0\sqrt{\frac{C}{L}}\sin\left(\frac{t}{\sqrt{LC}}\right)$$

$$V(t) = V_0\cos\left(\frac{t}{\sqrt{LC}}\right)$$

$$Z = \sqrt{\frac{L}{C}} \qquad \omega = \frac{1}{\sqrt{LC}}$$



A trapezoidal wave can be expressed by Fourier series (Guillemin's method)



$$\frac{i(t)}{I_L} = \frac{t}{a\tau} \quad , 0 \le t \le a\tau$$

$$\frac{i(t)}{I_L} = 1 \quad , a\tau \le t \le \tau - a\tau$$

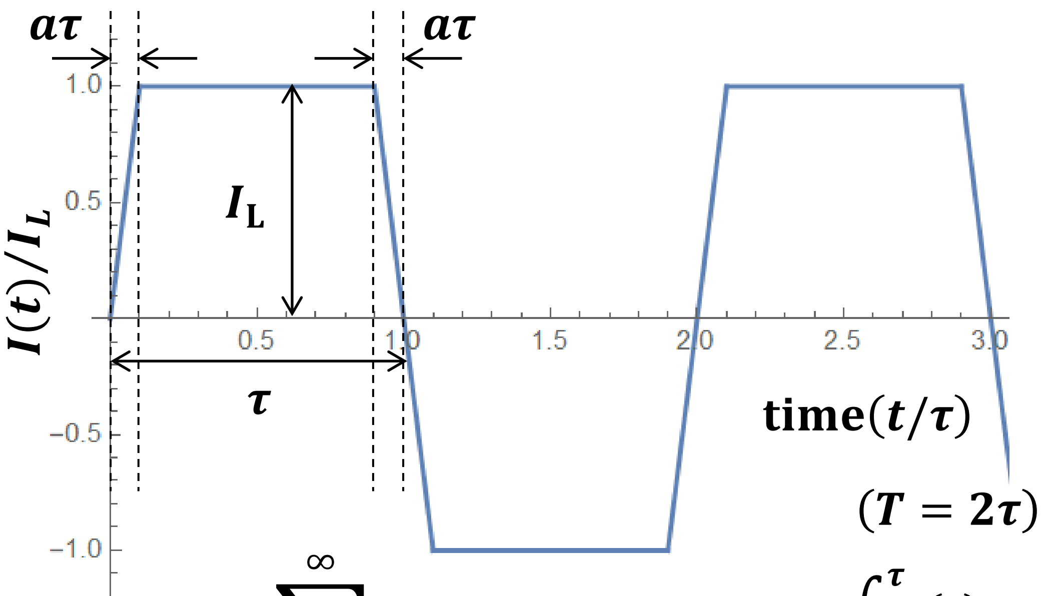
$$\frac{i(t)}{I_L} = \frac{\tau - t}{a\tau} \quad , \tau - a\tau \le t \le \tau$$

$$i(t) = I_L\left[\sum_{n=1}^{\infty} a_n \cos\left(\frac{n\pi t}{\tau}\right) + \sum_{n=1}^{\infty} b_n \sin\left(\frac{n\pi t}{\tau}\right)\right]$$

$$\text{where } a_n = \frac{2}{\tau}\int_0^{\tau} \frac{i(t)}{I_L} \cos\left(\frac{n\pi t}{\tau}\right) \, dt \equiv 0$$

$$\text{where } b_n = \frac{2}{\tau}\int_0^{\tau} \frac{i(t)}{I_L} \sin\left(\frac{n\pi t}{\tau}\right) \, dt$$

A trapezoidal wave can be expressed by Fourier series (Guillemin's method)



$$\frac{i(t)}{I_L} = \frac{t}{a\tau} \quad , 0 \le t \le a\tau$$

$$\frac{i(t)}{I_L} = 1 \quad , a\tau \le t \le \tau - a\tau$$

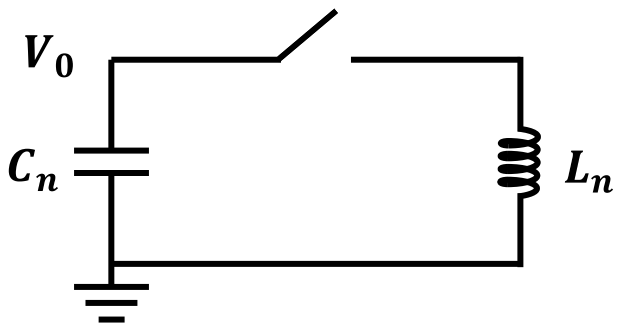
$$\frac{i(t)}{I_L} = \frac{\tau - t}{a\tau} \quad , \tau - a\tau \le t \le \tau$$

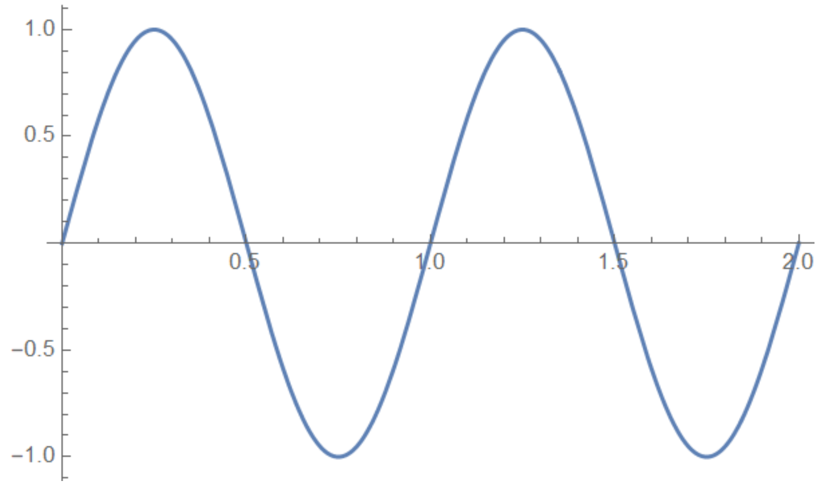
$$i(t) = I_L \sum_{n=1}^{\infty} b_n \sin\left(\frac{n\pi t}{\tau}\right)$$

$$b_n = \frac{2}{\tau}\int_0^{\tau} \frac{i(t)}{I_L} \sin\left(\frac{n\pi t}{\tau}\right) \mathrm{d}t = \frac{2}{\tau}\left[\int_0^{a\tau} \frac{t}{a\tau} \sin\left(\frac{n\pi t}{\tau}\right) \mathrm{d}t + \int_{a\tau}^{\tau - a\tau} \sin\left(\frac{n\pi t}{\tau}\right) \mathrm{d}t + \int_{\tau - a\tau}^{\tau} \frac{\tau - t}{a\tau} \sin\left(\frac{n\pi t}{\tau}\right) \mathrm{d}t\right]$$

$$b_n = \frac{4}{n\pi} \frac{\sin(n\pi a)}{n\pi a}, \text{where } n = 1, 3, 5 \ldots$$

The required inductance and capacitance are obtained by comparing LC output with the Fourier series





$$I_n(t) = V_0\sqrt{\frac{C_n}{L_n}}\sin\left(\frac{t}{\sqrt{L_nC_n}}\right)$$

$$L_n = \frac{Z_n\tau}{n\pi b_n} = \frac{V}{I_L}\frac{\tau}{n\pi b_n}$$

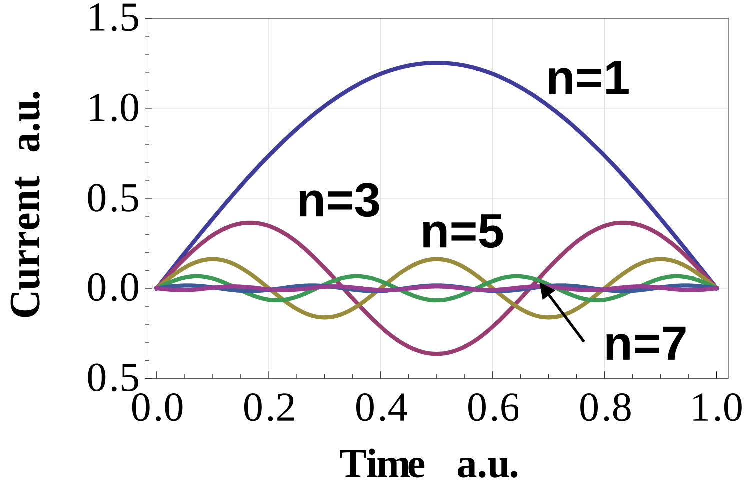
$$i(t) = I_L\sum_{n=1}^{\infty} b_n\sin\left(\frac{n\pi t}{\tau}\right)$$

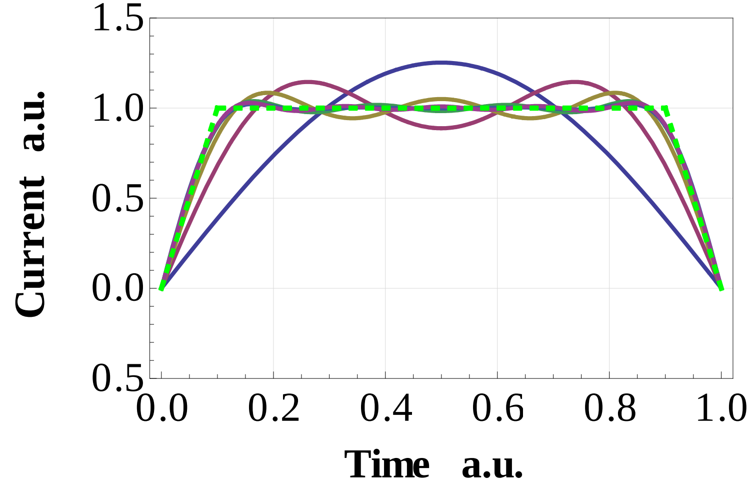
$$C_n = \frac{\tau b_n}{n\pi Z_n} = \frac{I_L}{V}\frac{\tau b_n}{n\pi}$$

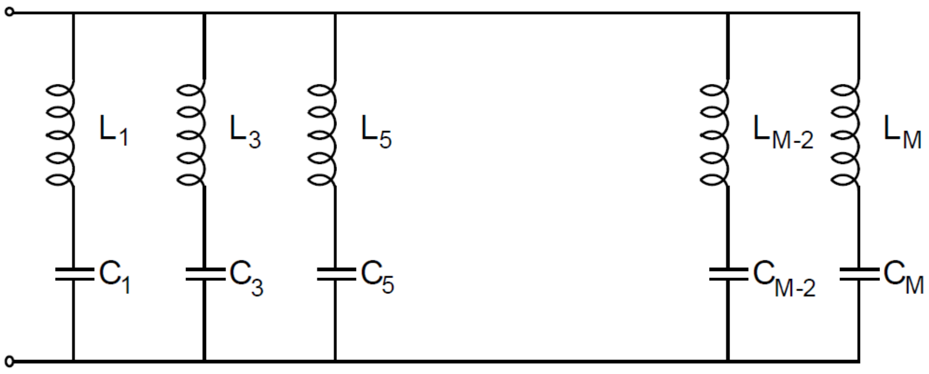
$$Z_n = \frac{V}{I_L}$$

$$b_n = \frac{4}{n\pi}\frac{\sin(n\pi a)}{n\pi a}, \text{where } n = 1, 3, 5\ldots$$

A trapezoidal current output can be generated using Guillemin’s pulse-forming networks





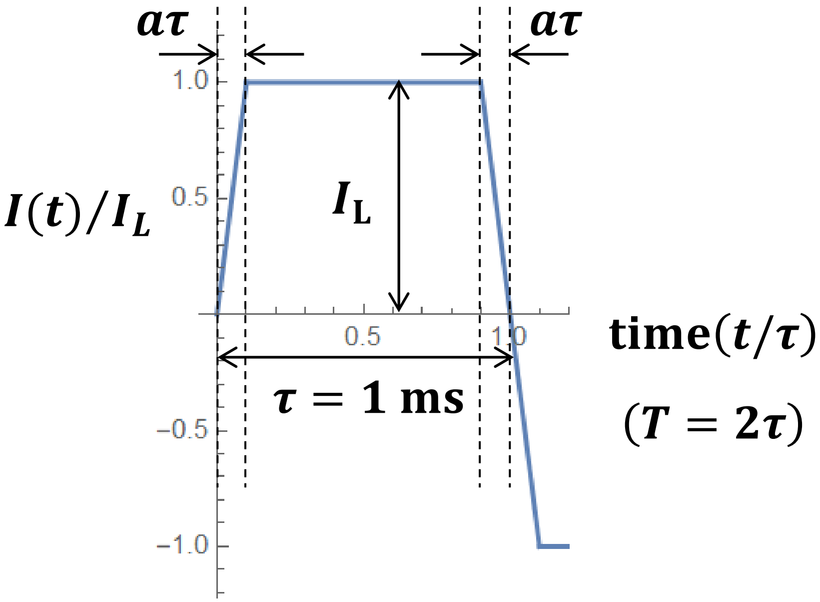


$$I(t) = I_L \Sigma b_n \mathrm{Sin}\left(\frac{n\pi t}{\tau}\right)$$

$$b_n = \frac{4}{n\pi}\frac{\mathrm{Sin}(n\pi a)}{n\pi a}$$

$$L_n = \frac{Z\tau}{n\pi b_n} \quad C_n = \frac{\tau b_n}{n\pi Z} \quad Z = \frac{V}{I_L}$$

Fourier components of τ=1 ms, a=0.1



$$i(t) = I_L \sum_{n=1}^{\infty} b_n \sin\left(\frac{n\pi t}{\tau}\right)$$

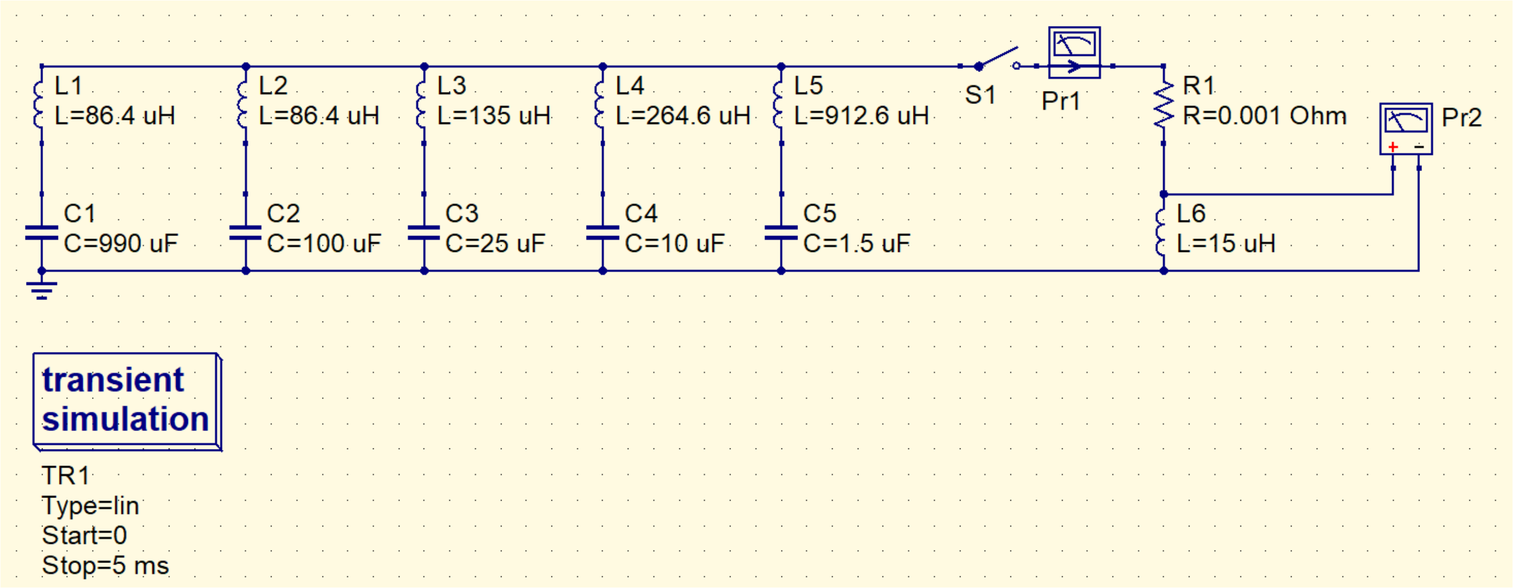
$$b_n = \frac{4}{n\pi}\frac{\sin(n\pi a)}{n\pi a}, \text{where } n = 1, 3, 5\ldots$$

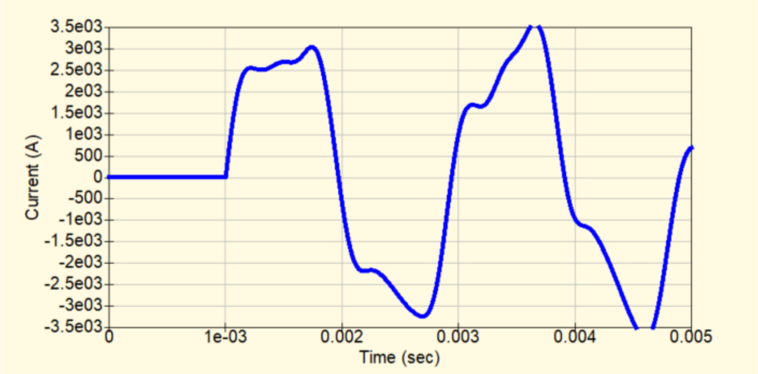
n	#/
b1	1.2524
b3	0.3643
b5	0.1621
b7	0.069
b9	0.0155

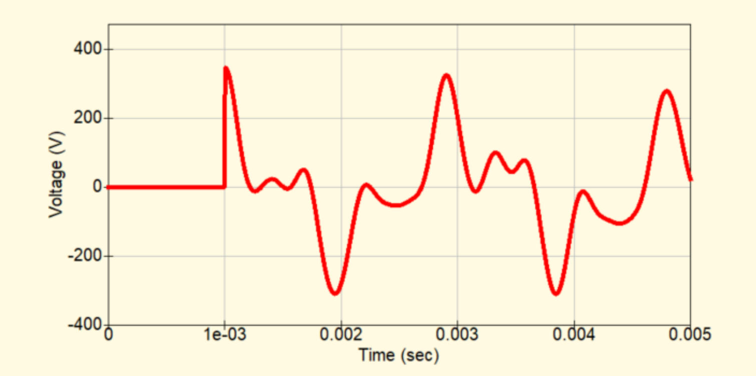
Coils with 8 turns and a PFN charged to 1 kV will be used

I (kA)	V (kV)		1	2	3	4	5	E (kJ)	% to 100 J
20	2	L(uH)	25.4	26.1	39.3	68.0	228.7	9.0	1.1 %
		C(uF)	3986.5	386.5	103.2	30.4	5.5		
20	1	L(uH)	12.7	14.6	19.6	34.0	114.4	4.5	2.2 %
		C(uF)	7973.0	773.1	206.4	60.9	10.9		
2.5	2	L(uH)	203.3	233.0	314.2	543.7	1830.0	1.1	8.9 %
		C(uF)	498.3	48.3	12.9	3.8	0.7		
2.5	1	L(uH)	101.7	116.5	157.1	271.8	915.0	0.6	17.7 %
		C(uF)	996.6	96.6	25.8	7.6	1.4		

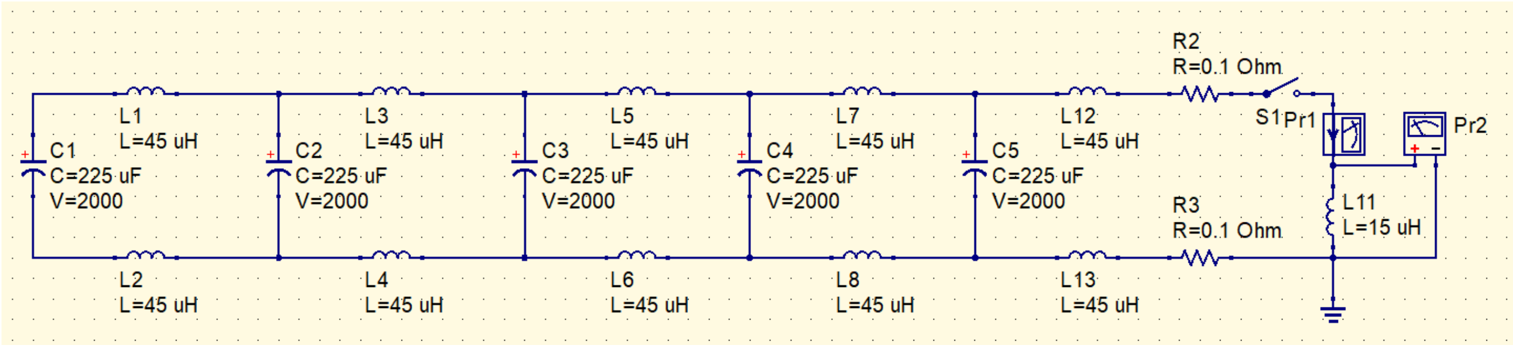
A square pulse with a flat top of 2.5 kA can be generated







A simple PFN with constant C and L in all stages can also be used



$$C \equiv \bar{C} = \frac{1}{N}\sum_{n=1}^{N} C_n = 225\mu\text{F}$$

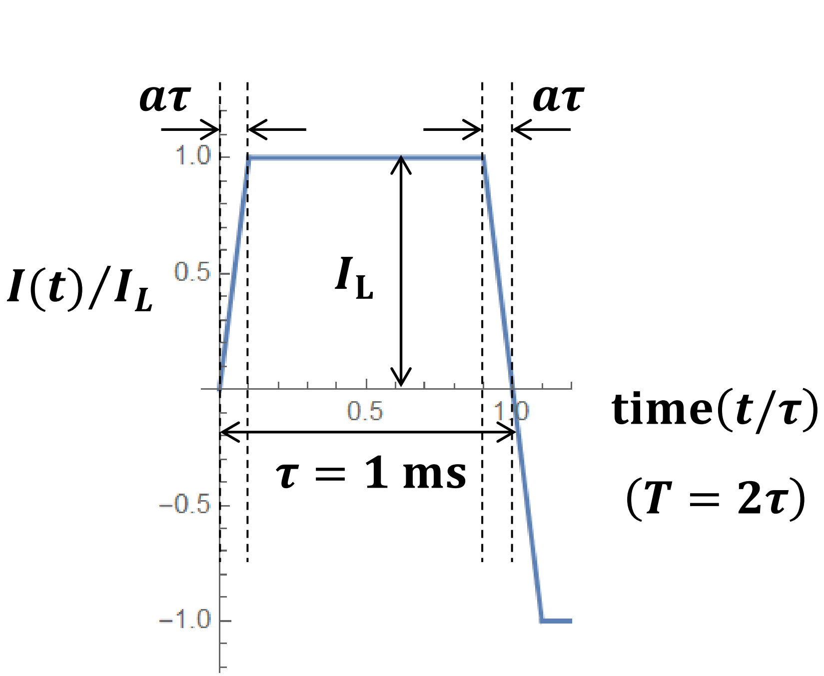
$$L_n = 2nL + L_L \approx 2nL$$

$$\omega_n = \frac{1}{\sqrt{L_n C}} \approx \frac{1}{\sqrt{2nLC}}$$

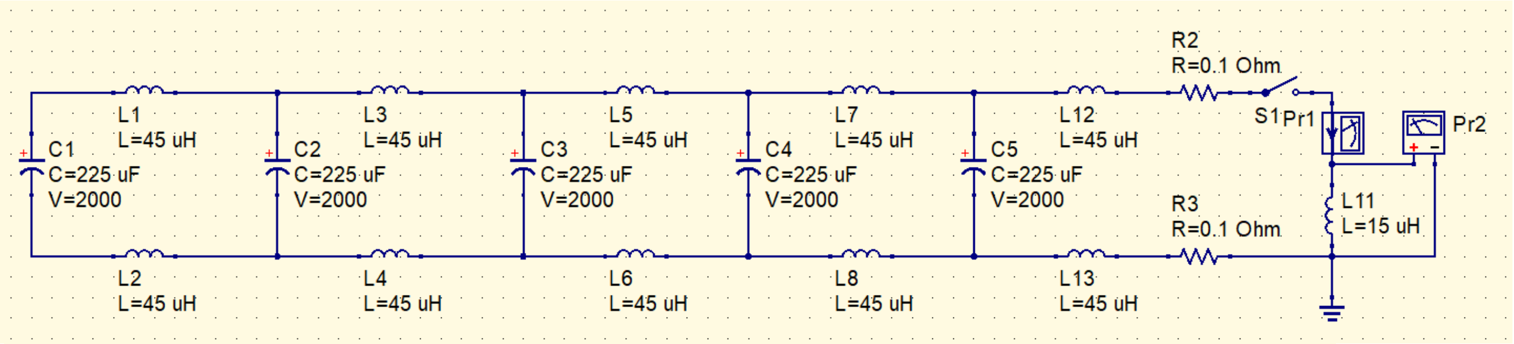
- **For 5 stages:**

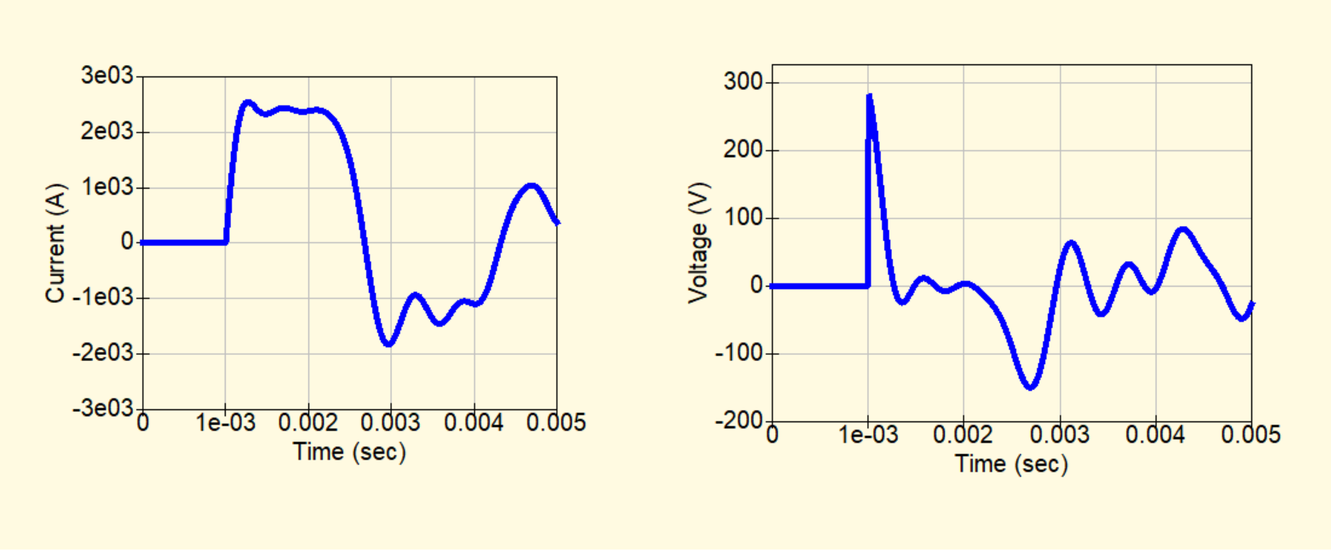
$$\omega_5 = \frac{2\pi}{T} = \frac{\pi}{\tau} = \frac{\pi}{1\text{ms}}$$

$$L = 45\mu\text{H}$$



The energy coupling efficiency is lower using the simple PFN

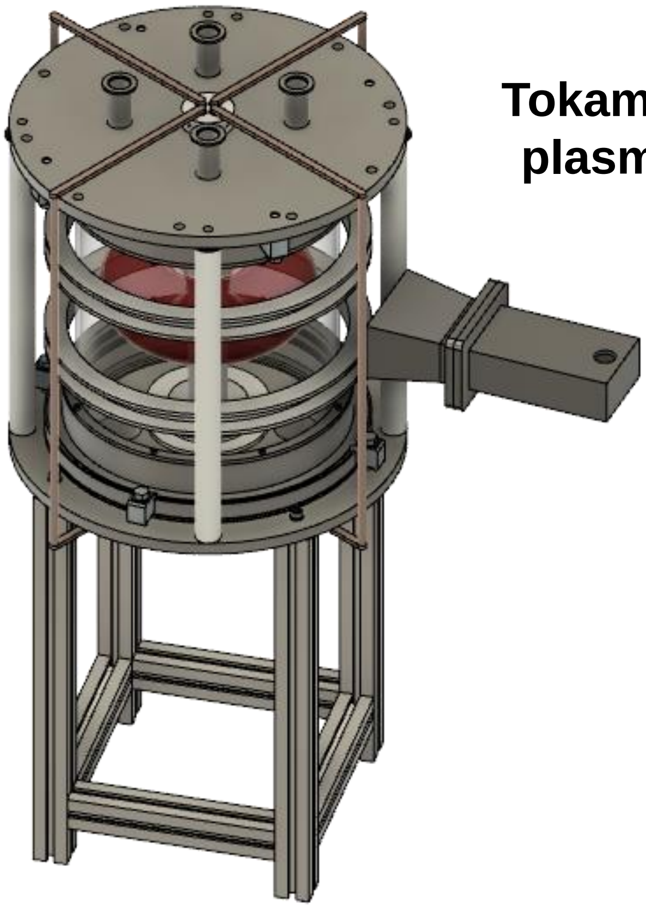


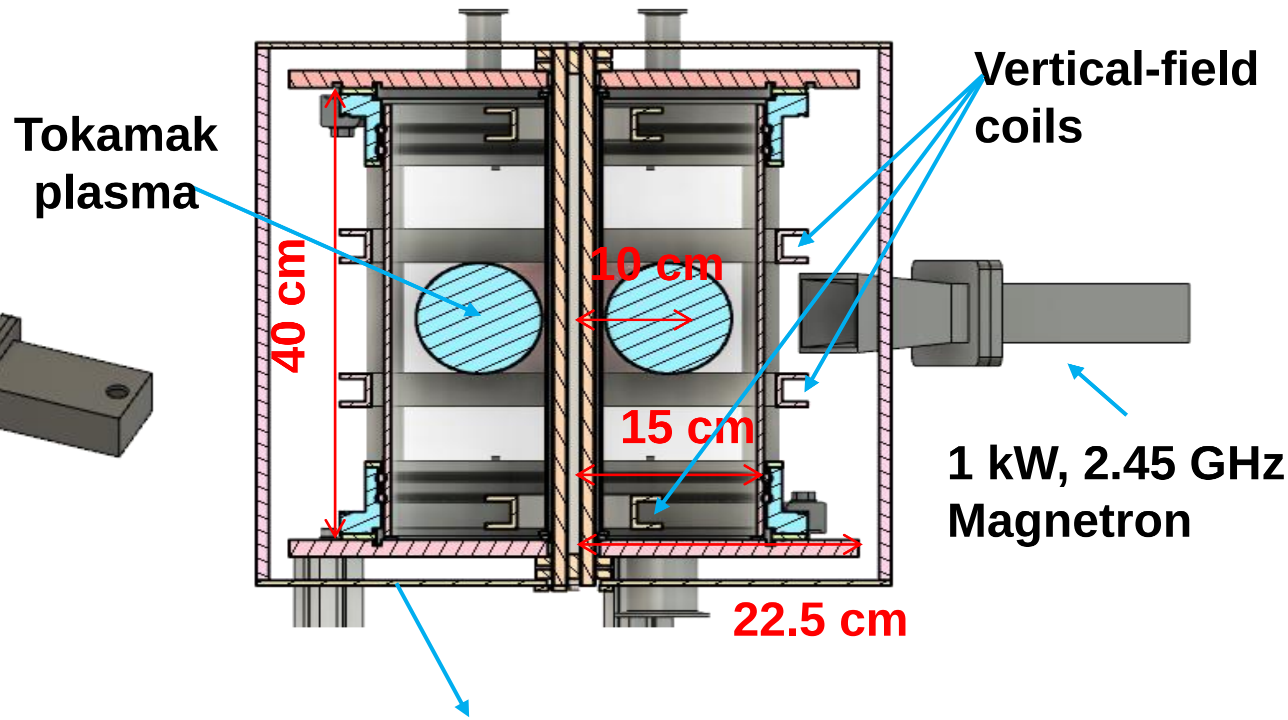


$$E = \frac{1}{2}CV^2 = 2.25\text{kJ}$$

- **Only 4.4 % of the energy is transferred to magnetic energy.**

Mini-spherical tokamak

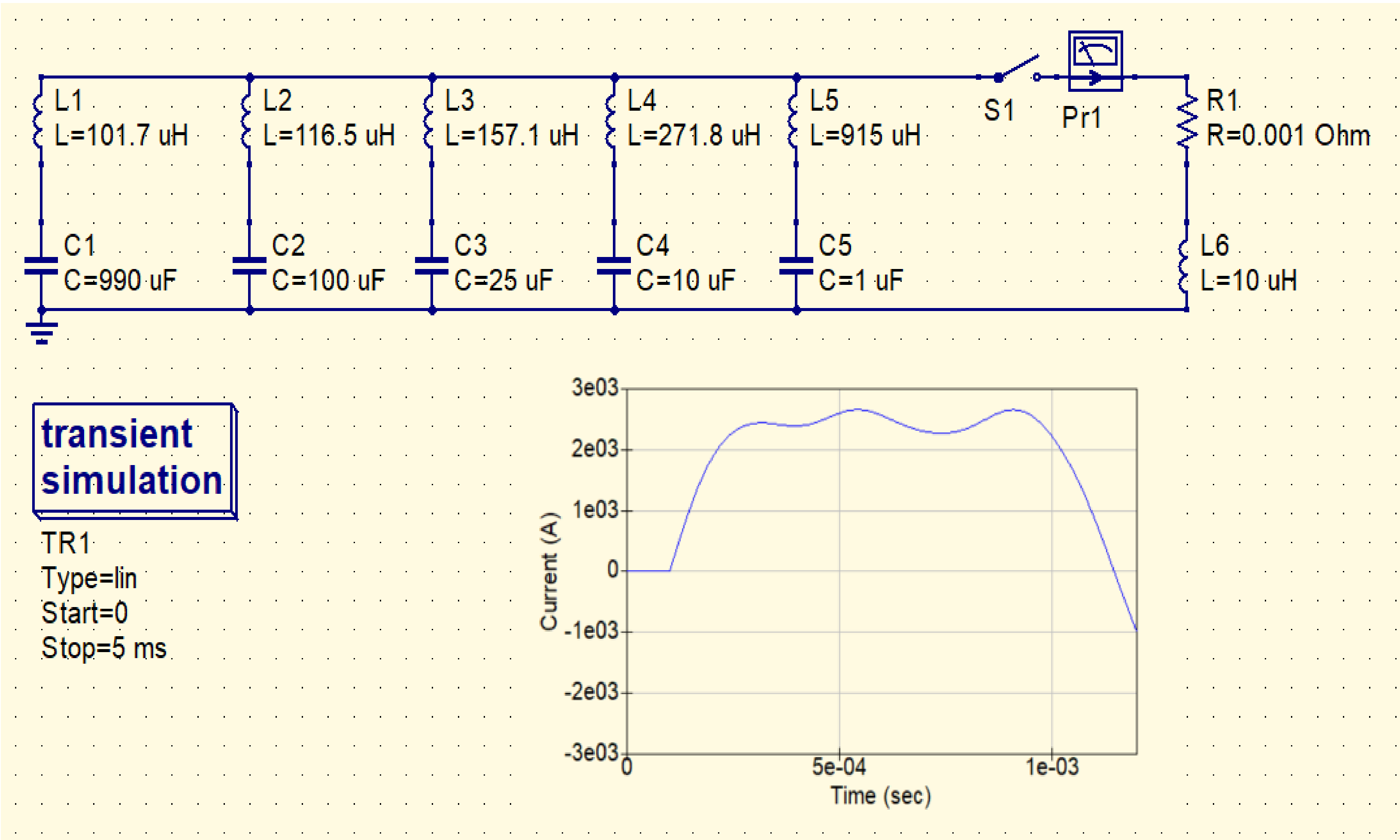




4 toroidal-field coil connected in series. 1 ms, 2.5 kA pulsed-current.

B=876 G @ 4.6 cm will be used for ECR heating.

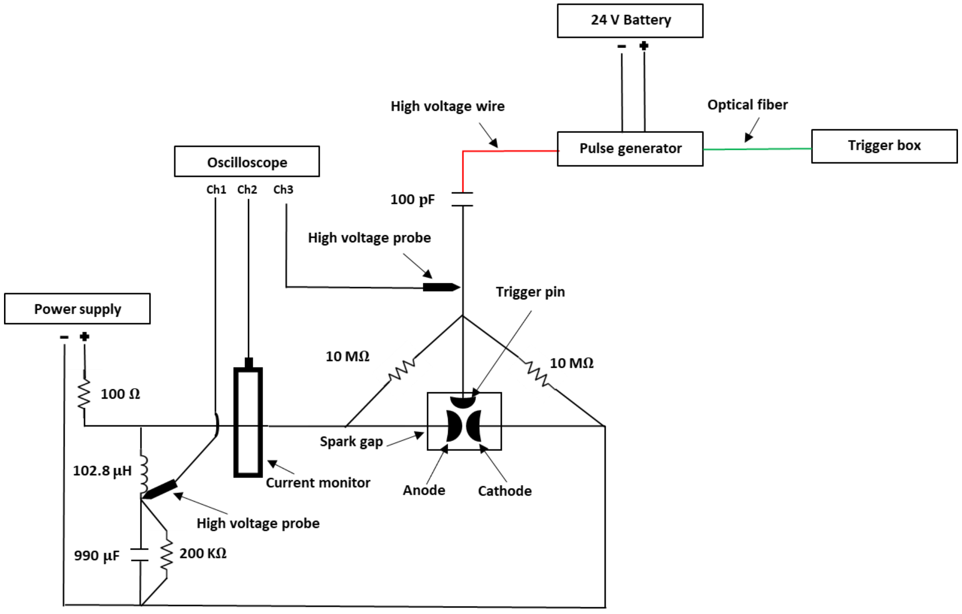
A square pulse of 2.5-kA current output with duration of 1 ms can be provided



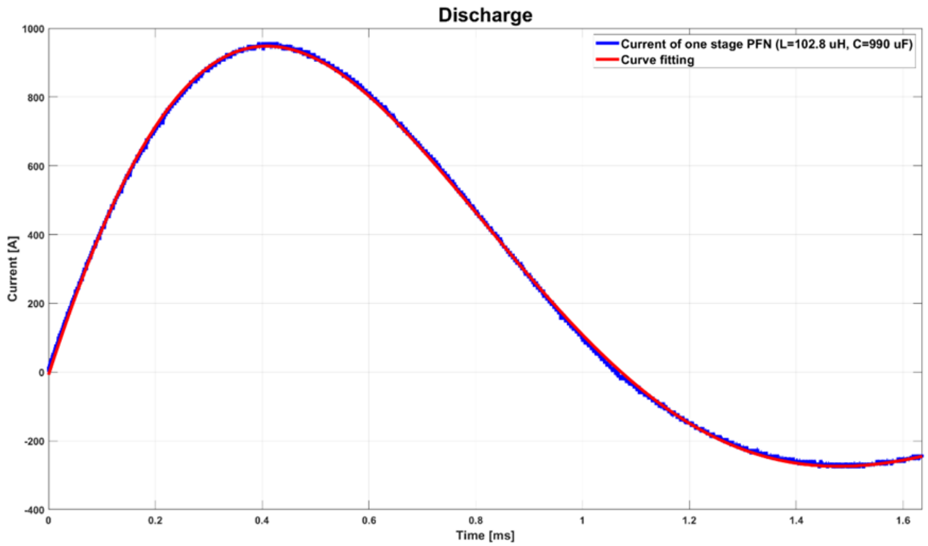
The actual components were determined by what we could get

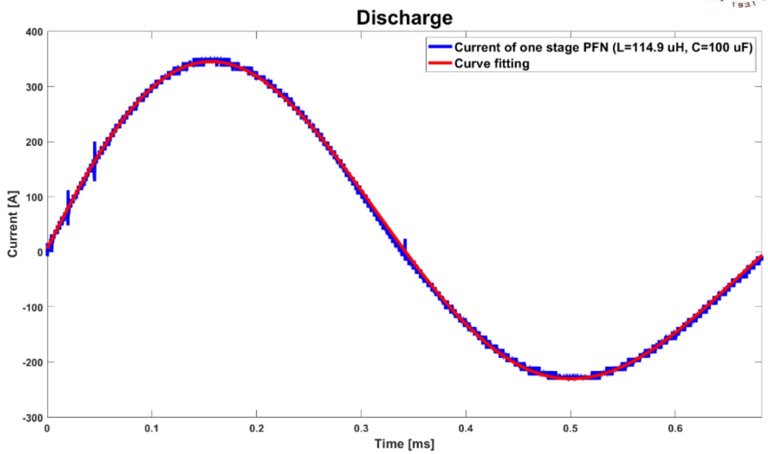
- **Design:**
- **Built:**

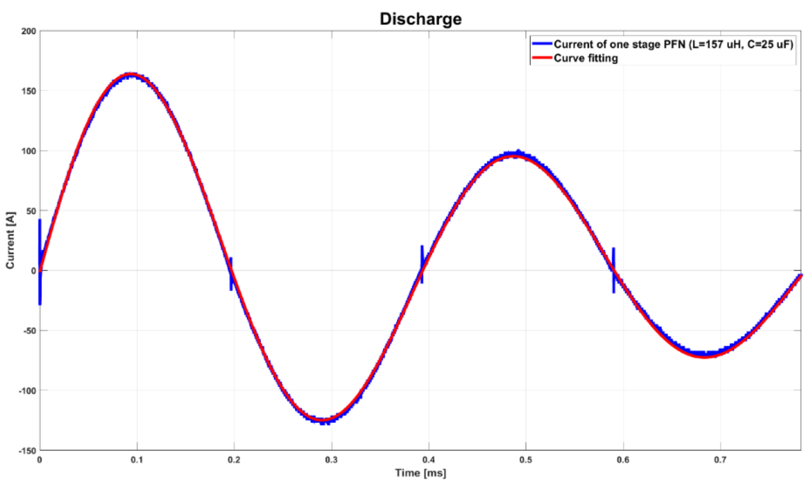
	I (kA)	V (kV)		1	2	3	4	5
Design	2.5	1	L(uH)	101.7	116.5	157.1	271.8	915.0
			C(uF)	996.6	96.6	25.8	7.6	1.4
Built	2.5	1	L(uH)	102.8	114.9	157	270	-
			C(uF)	990	100	25	10	-

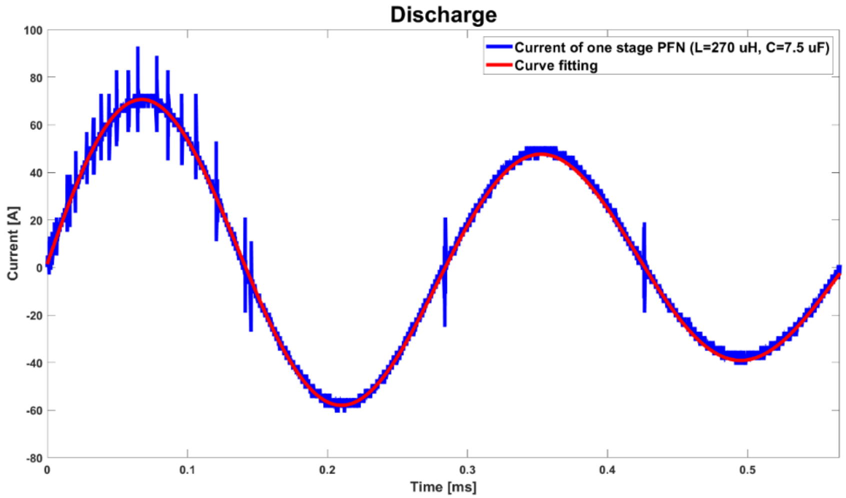


Discharge current measurements

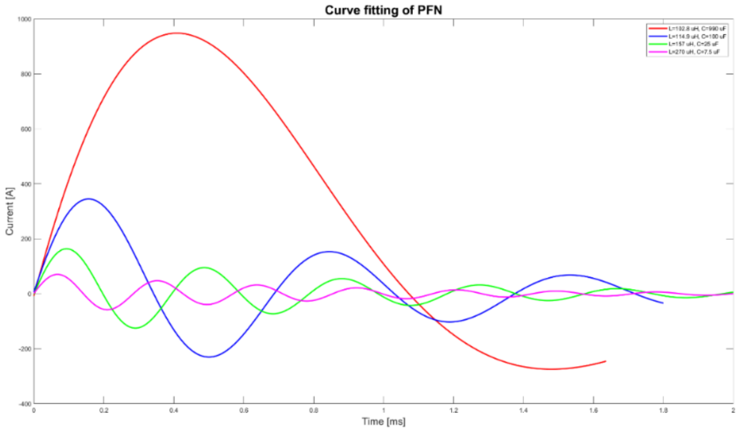




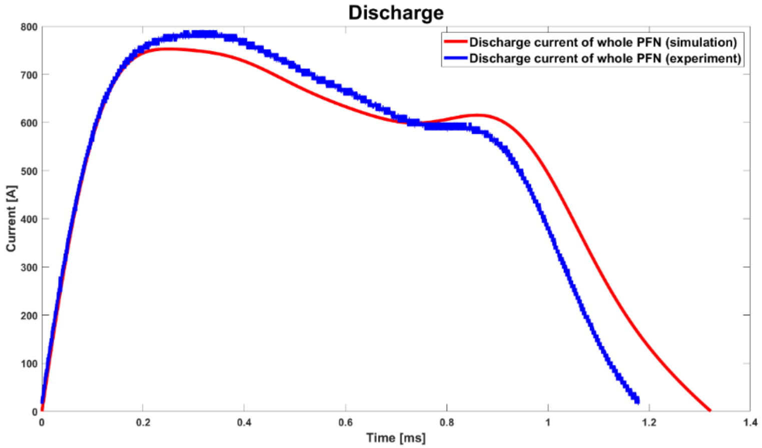


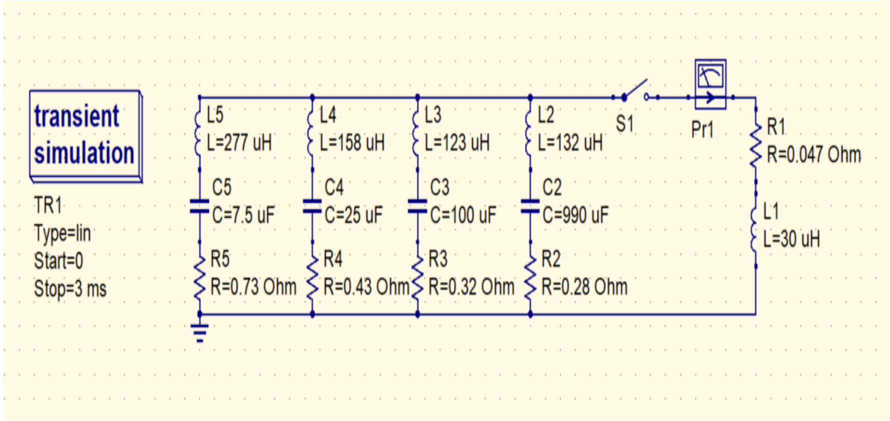


Resistant played an important role



Stage	C (theory)	L (theory)	L (measure)	R (measure)
1	990 (uF)	102.8 (uH)	132±4 (uH)	0.28±0.01 (Ω)
2	100 (uF)	114.9 (uH)	123±0.4 (uH)	0.32±0.02 (Ω)
3	25 (uF)	157 (uH)	158±1 (uH)	0.43±0.01 (Ω)
4	7.5 (uF)	270 (uH)	277±7 (uH)	0.73±0.03 (Ω)



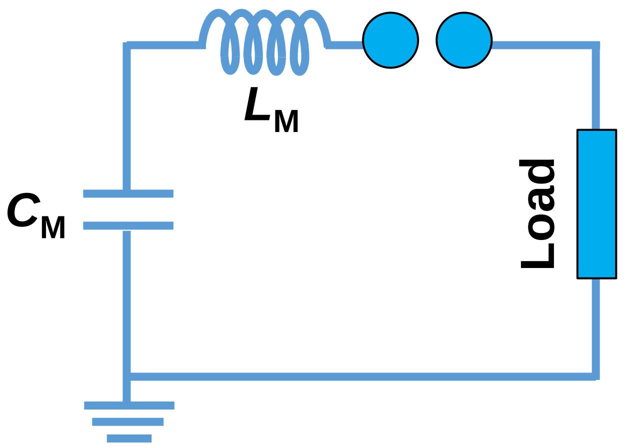


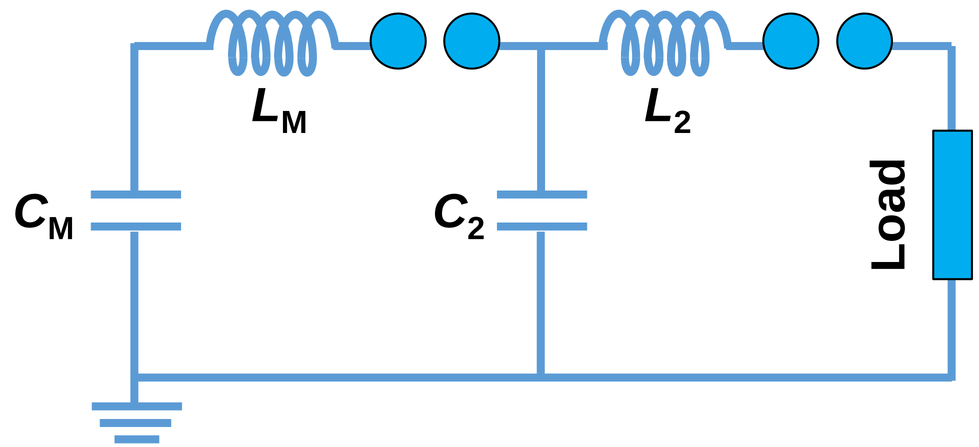
Outlines

- Switches
  - Closing switches: the switching process is associated with voltage breakdown across an initially insulant element.
  - Opening switches: the switching process is associated with a sudden growth of its impedance.
- **Pulse-forming lines**
  - Blumlein line
  - Pulse-forming network
  - **Pulse compressor**
- Pulse transmission and transformation

Capacitor load

- **Pulse compression scheme: a charged capacitor can transfer almost all of its energy to an uncharged capacitor if connected through an inductor.**
- **Output voltage can be doubled in a peaking circuit.**





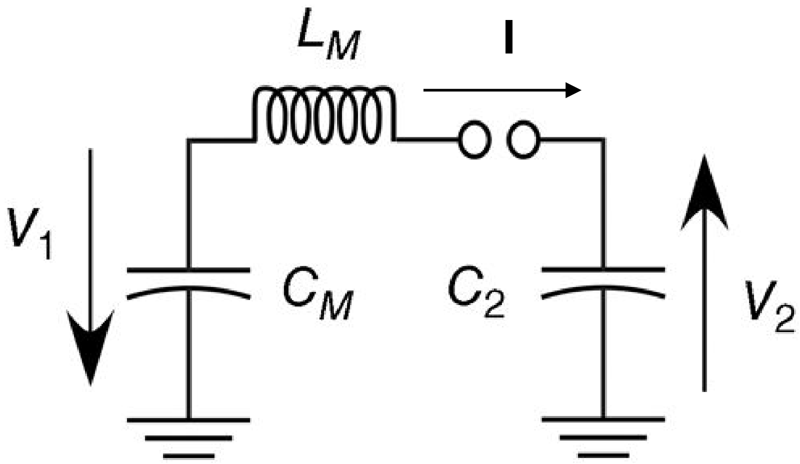
$$I_0 = \frac{V_0}{\sqrt{L_M/C_M}} \quad \omega_0 = \frac{1}{\sqrt{L_M C_M}}$$

$$I_2 = \frac{V_0}{\sqrt{L_2/C_2}} \quad \omega_2 = \frac{1}{\sqrt{L_2 C_2}}$$

$L_M > L_2$ => $I_M < I_2$ $\omega_M < \omega_2$ $T_M > T_2$

Capacitor load

$$V_1 - L_M \frac{\mathrm{dI}}{\mathrm{dt}} = V_2$$



$$V_1 = V_M - \frac{1}{C_M}\int I\,\mathrm{d}t \qquad V_M = \mathrm{NV_0}$$

$$V_2 = \frac{1}{C_2}\int I\,\mathrm{d}t$$

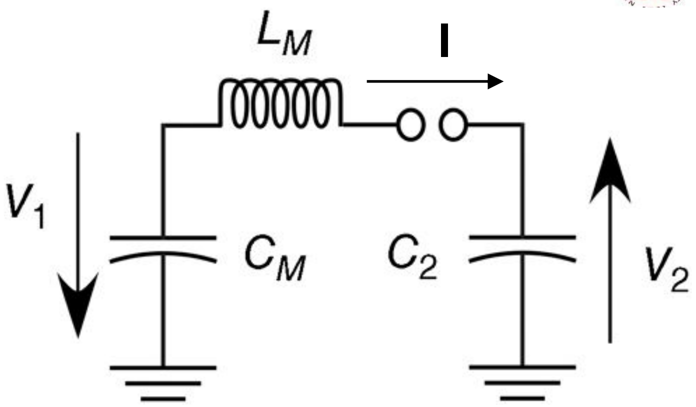
$$V_M - \frac{1}{C_M}\int I\,\mathrm{d}t - L_M\frac{\mathrm{dI}}{\mathrm{dt}} = \frac{1}{C_2}\int I\,\mathrm{d}t$$

$$-\frac{1}{C_M}I - L_M\frac{d^2I}{\mathrm{dt}^2} = \frac{1}{C_2}I \qquad L_M\frac{d^2I}{\mathrm{dt}^2} + \left(\frac{1}{C_M}+\frac{1}{C_2}\right)I = 0$$

$$\frac{d^2I}{\mathrm{dt}^2} + \frac{1}{L_M C_{\mathrm{eff}}}I = 0 \qquad \frac{1}{C_{\mathrm{eff}}} = \frac{1}{C_M}+\frac{1}{C_2} \qquad \omega = \sqrt{\frac{1}{L_M C_{\mathrm{eff}}}}$$

$$I = \alpha\sin(\omega t) + \beta\cos(\omega t)$$

Capacitor load



$$I = \alpha\sin(\omega t) + \beta\cos(\omega t)$$

$$I(t=0) = 0 => \beta = 0$$

$$I = \alpha\sin(\omega t)$$

$$\frac{dI}{dt} = \alpha\omega\cos(\omega t)$$

$$L_M \left.\frac{dI}{dt}\right|_{t=0} = L_M\alpha\omega = V_M \qquad \alpha = \frac{V_M}{L_M\omega}$$

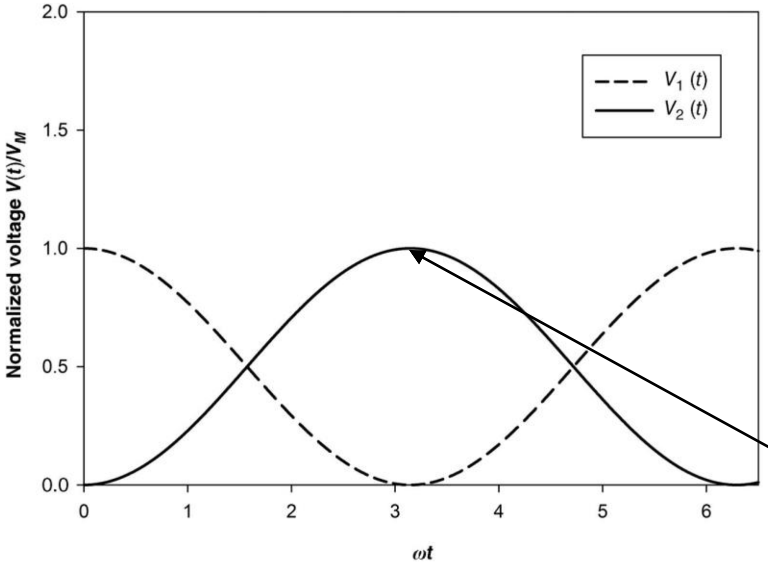
$$I(t) = \frac{V_M}{L\omega}\sin(\omega t)$$

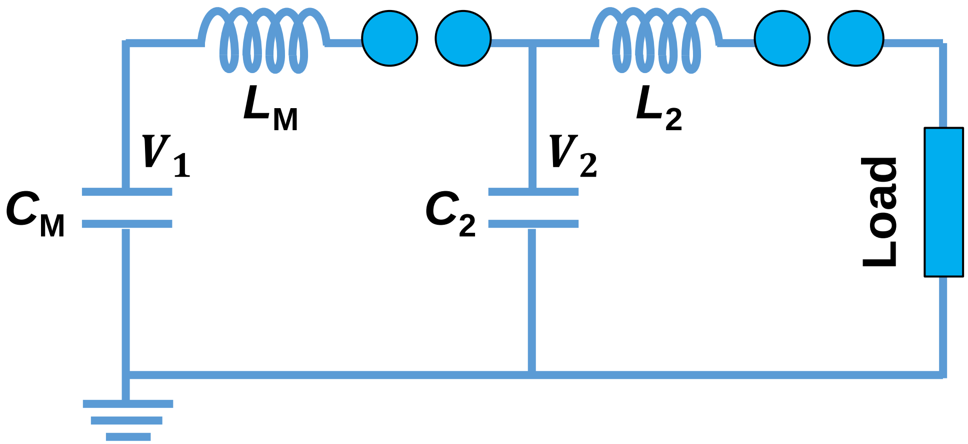
$$V_1 = V_M - \frac{1}{C_M}\int_0^t \frac{V_M}{L\omega}\sin(\omega t)\,dt = V_M - \frac{V_M C_2}{C_M + C_2}[1 - \cos(\omega t)]$$

$$V_2 = \frac{1}{C_2}\int_0^t \frac{V_M}{L\omega}\sin(\omega t)\,dt = \frac{V_M C_M}{C_M + C_2}[1 - \cos(\omega t)] \qquad \left.\frac{V_2}{V_M}\right|_{max} = \frac{2C_M}{C_M + C_2}$$

for $C_2 \sim C_M, \frac{V_2}{V_M} \sim 1$

Pulse compression scheme: $C_2 \sim C_M$





Energy is fully transferred to the 2nd cap, i.e., intermediate storage capacitor.

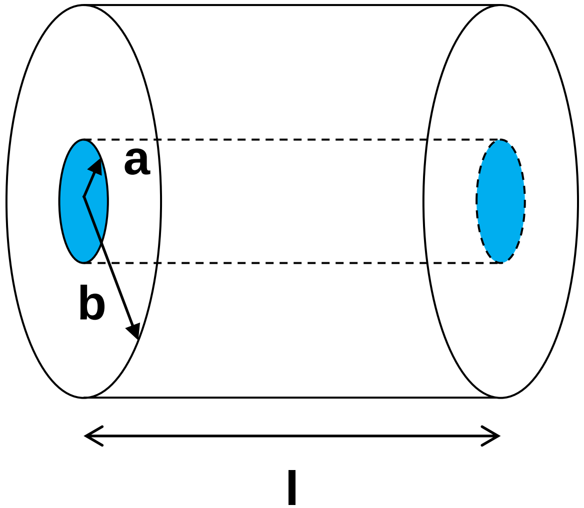
$$V_1 = V_M - \frac{V_M C_2}{C_M + C_2}[1 - \cos(\omega t)] \approx V_M - \frac{V_M}{2}[1 - \cos(\omega t)]$$

$$V_2 = \frac{V_M C_M}{C_M + C_2}[1 - \cos(\omega t)] \approx \frac{V_M}{2}[1 - \cos(\omega t)]$$

$$\text{For } t = \frac{\pi}{\omega}, \qquad V_1 \approx 0, \qquad V_2 \approx V_M$$

Water is commonly used as the dielectric material for the intermediate capacitor

$$C = \frac{2\pi\epsilon_r\epsilon_0}{\ln(b/a)} l \qquad \text{For } \frac{b}{a} = \frac{1}{0.9} \approx 1.1$$



- The gap between two cylinders need to be able to handle the high voltage.

$$\text{Air: } \epsilon_r = 1 \Rightarrow \frac{C}{l} = 0.5 \times 10^{-9}\, F/m$$

$$\text{Water: } \epsilon_r = 80 \Rightarrow \frac{C}{l} = 4 \times 10^{-8}\, F/m$$

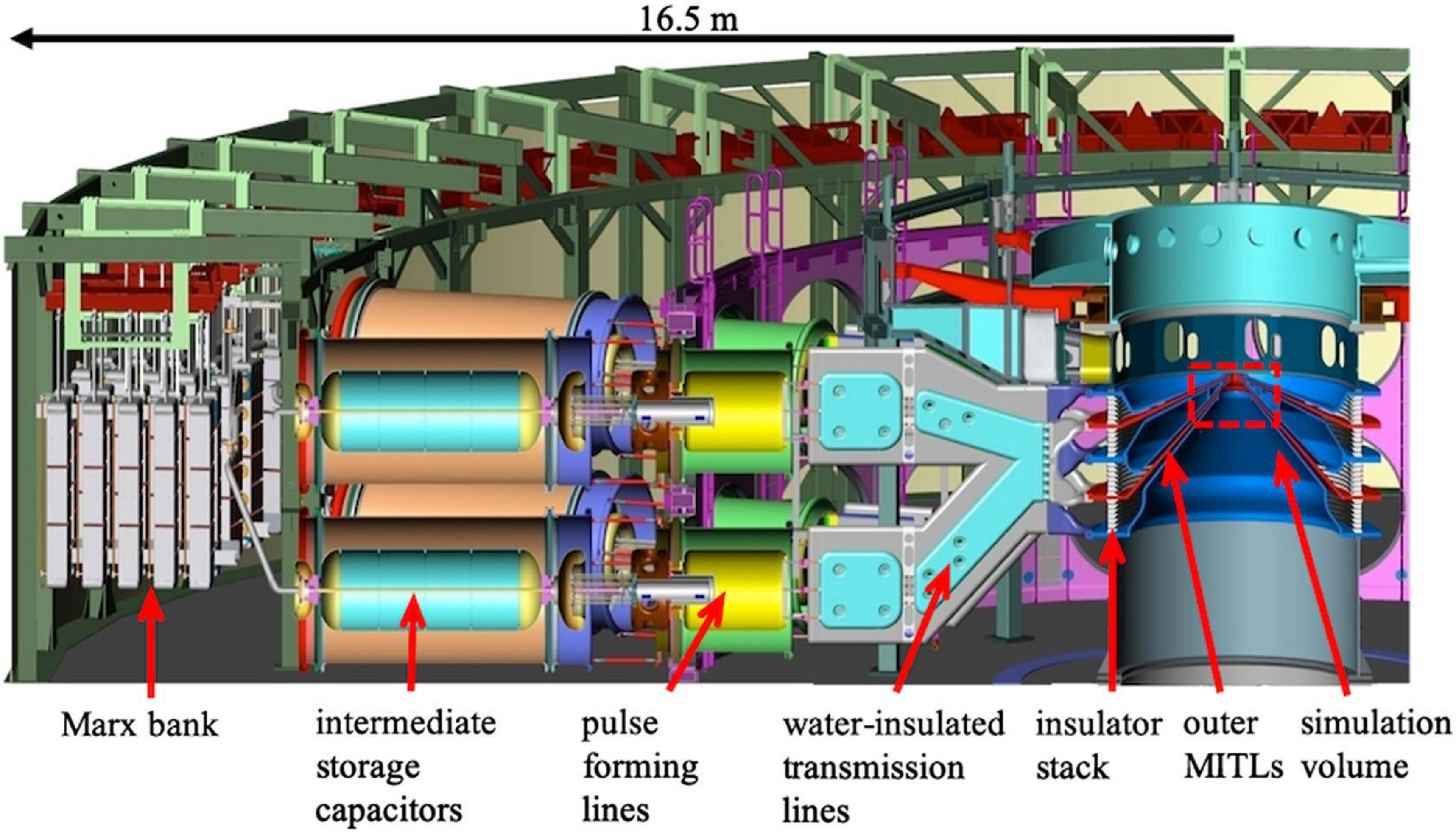
Ex: KALIF, bipolar Marx generator, charged up to ±100 kV. $V_{M,out}$=5 MV.

$$C_M = \frac{0.5\mu\text{F}}{25} = 25\text{nF}$$

$$\text{Using air: } \quad \mathrm{l} = \frac{25 \times 10^{-9}}{0.5 \times 10^{-9}} = 50\text{ m}$$

$$\text{Using water: } \quad \mathrm{l} = \frac{25 \times 10^{-9}}{4 \times 10^{-8}} = 0.625\text{ m}$$

Intermediate storage capacitors can be used to compress the pulse

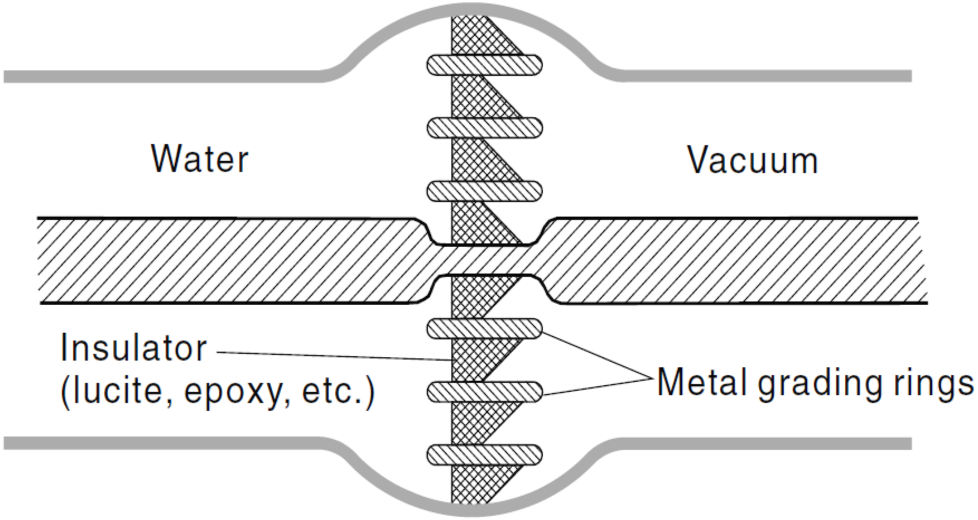


Outlines

- Switches
  - Closing switches: the switching process is associated with voltage breakdown across an initially insulant element.
  - Opening switches: the switching process is associated with a sudden growth of its impedance.
- Pulse-forming lines
  - Blumlein line
  - Pulse-forming network
  - Pulse compressor
- **Pulse transmission and transformation**

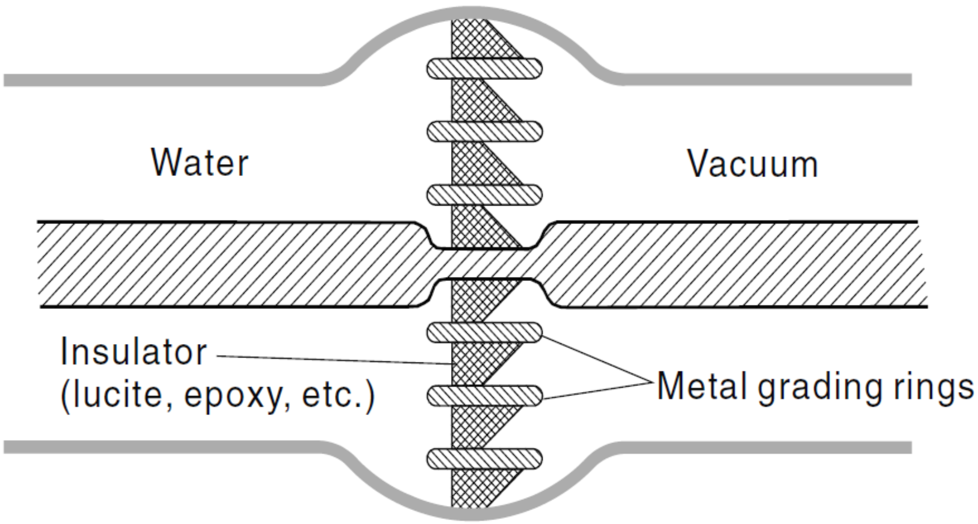
Insulating interface separating the vacuum section and the liquid dielectric is needed

- **Some tasks in science and technology required brightness of intense pulsed radiation > 100 TW/cm^2-Sr. With E > 1 MJ, electric power > 100 TW, electric power flux density > 100TW/m^2 are needed.**
- **Vacuum environment is required.**
- **High-voltage pulse must enter a vacuum vessel hosting the source through an insulating interface separating the liquid dielectric from the vacuum section.**



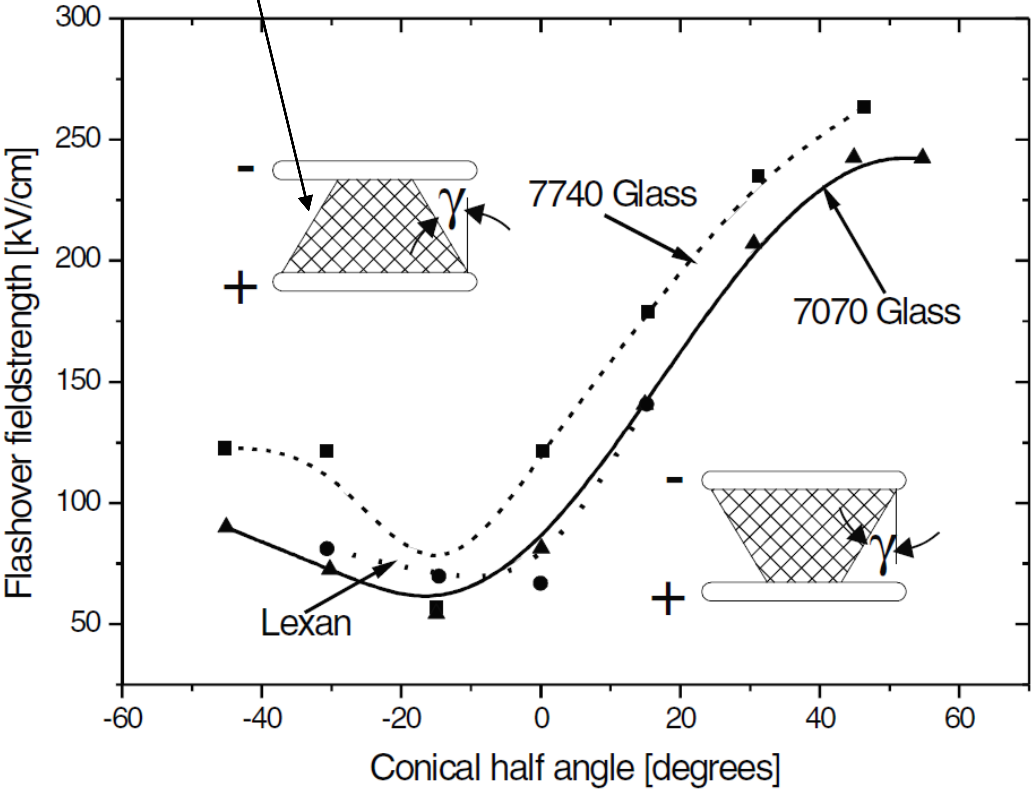
The interface consists of insulating rings separated by metallic grading rings

- **The metal grading rings are used to distribute the potential homogeneously over the interface on the vacuum surface.**
- **The metallic and dielectric rings are sealed to hold the high vacuum either by O-rings or by Metal-to-dielectric bond.**
- **Sparking on the surface on the vacuum side is more important.**
- **Electrons may be produced by field emission on metallic surfaces.**



The side surface of the dielectric material is tilted to prevent flash over

- **Out gassing: gas from the "absorbs" released by electron bombardment.**
- **Electron avalanches may occur with the tangential electric field from the space charge on insulator.**

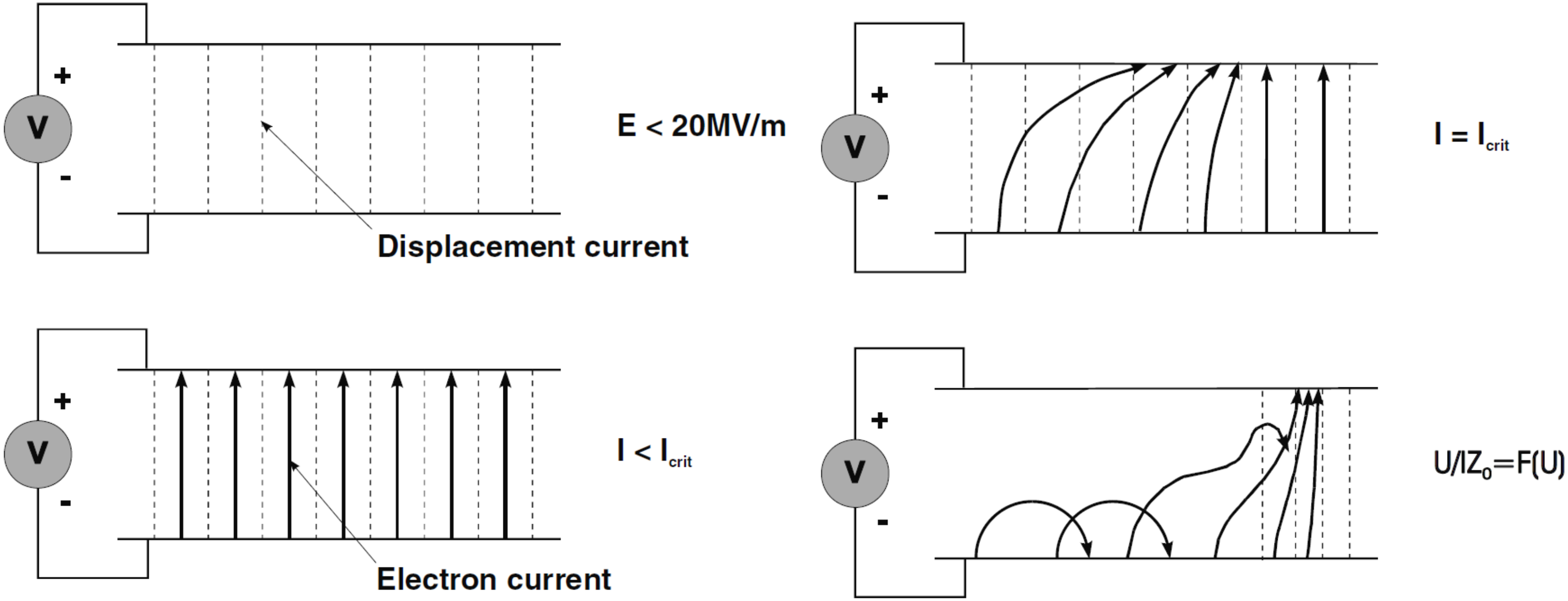


- **Dielectric-vacuum interface is the weakest element of a high-voltage pulse line under E-field stress.**

$$E_{\mathrm{DB}} = \frac{7 \times 10^5}{t^{1/6} A^{1/10}} (V/m)$$

- **t: time when E > 87% E_{max}.**
- **For t=10 ns, E_{max}=20MV/m, Max power density that can be delivered is 1 TW/m^2.**

Self-magnetic insulation

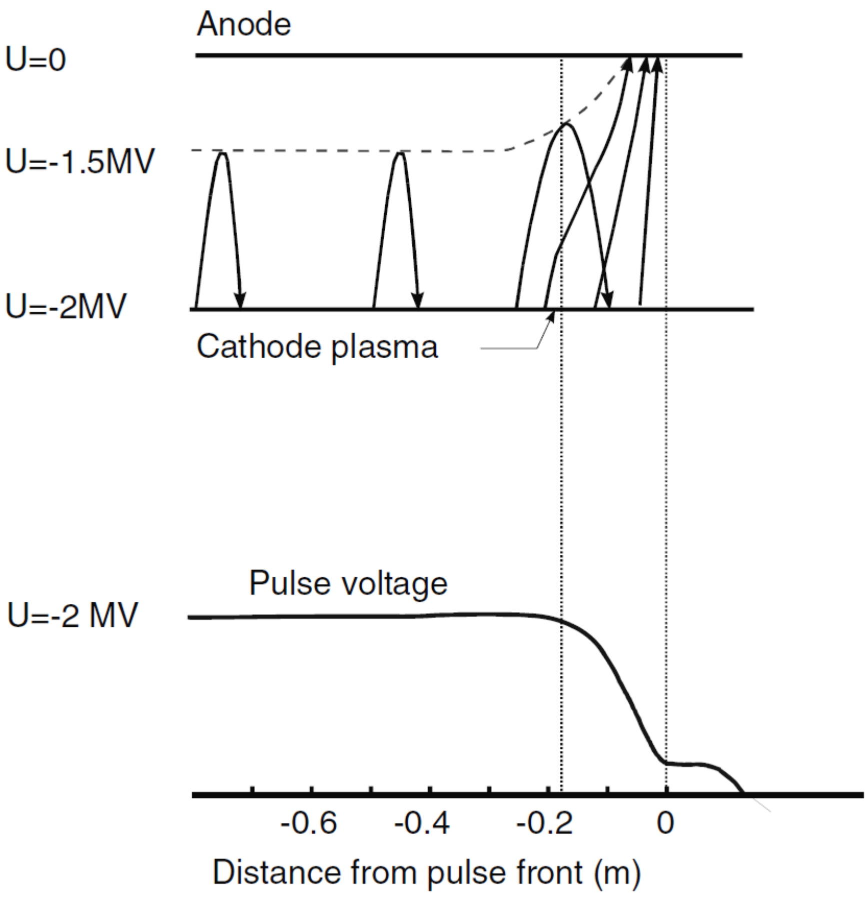


- For E > 20 MV/m, homogeneous plasma layer is generated within a few nanosecond.
- For I > I_{crit}, electron orbits can no longer reach the anode => more and more sections are insulated. => An electron sheath forms on the negative conductor.

Electromagnetic shock wave is formed

- **The propagation velocity of the loss front is less than the speed of light, c.**

- **As long as the voltage ramp remains below the breakdown threshold, the wave propagates at the speed of light.**



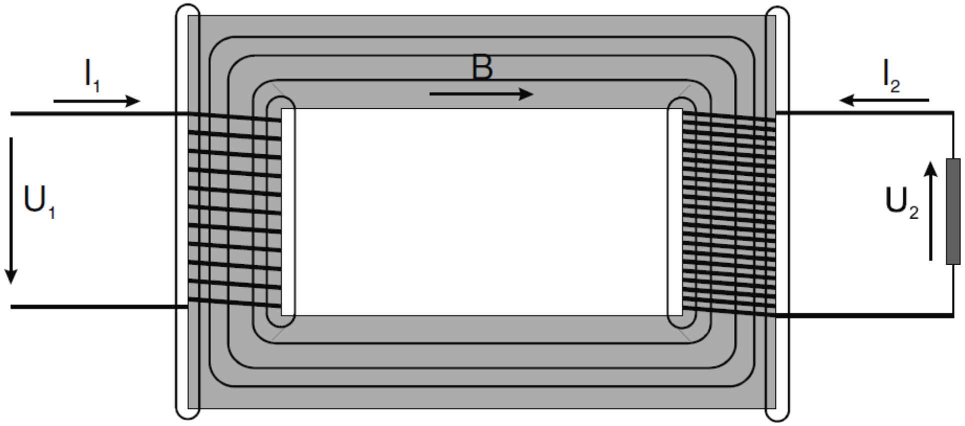
Pulse transformers

- **High-voltage transformers: used for transformation of current, voltage, impedance, polarity inversion, insulation and coupling between circuits at different potentials.**
- **Based on magnetic coupling between two conducting circuits.**
- **Perfect or ideal transformer: no ohmic losses, no eddy currents, without hysteresis and stray field => magnetic flux goes completely through both the primary and second coil.**
- **Faraday's law:**

$$U_1 = N_1 \frac{d\phi}{dt}$$

$$U_2 = -N_2 \frac{d\phi}{dt}$$

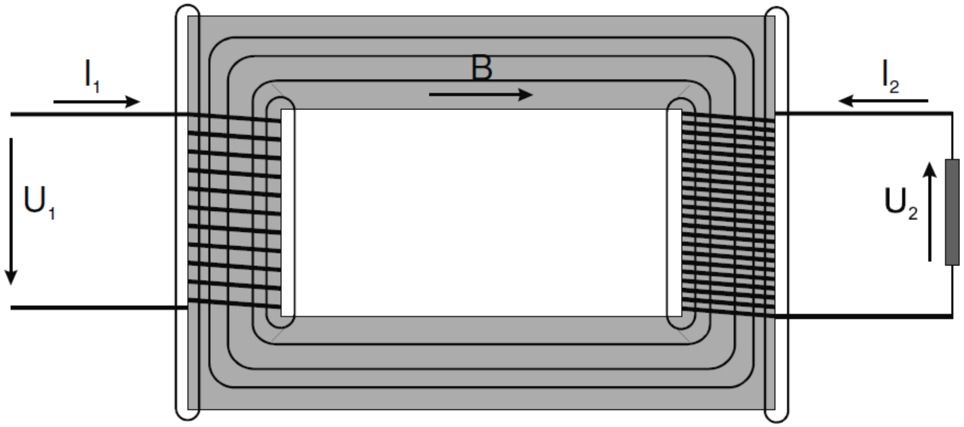
$$\frac{U_2}{U_1} = -\frac{N_2}{N_1}$$



The transformer rise the voltage but reduce the current

$$U_1 = N_1 \frac{d\phi}{dt} \qquad \frac{U_2}{U_1} = -\frac{N_2}{N_1}$$

$$U_2 = -N_2 \frac{d\phi}{dt}$$



- **For open circuit, i.e. secondary coil is open => ϕ is caused by i_1 only:**

$$i_{10} = \frac{U_1}{i\omega L_1}$$

- **If a load of complex impedance Z is connected to the secondary coil:**

$$i_2 = \frac{U_2}{Z} \qquad N_2 i_2 = N_1 i_1'$$

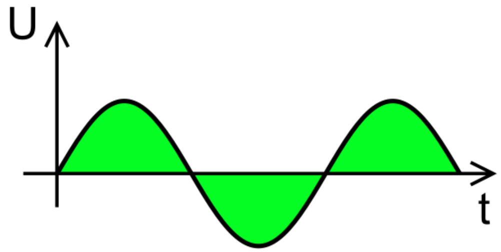
Additional flux from the secondary coil is compensated from primary coil.

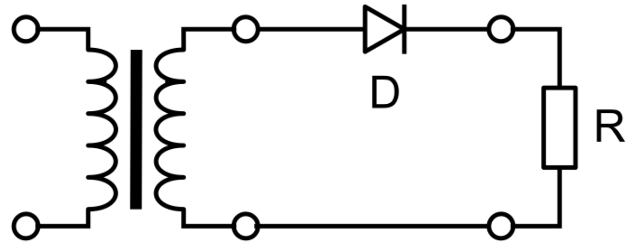
$$i_1' = i_{10} + i_1' = i_{10} - \frac{N_2}{N_1} i_2 \qquad \text{Power} = (i_1' - i_{10})U_1 = -\frac{N_2}{N_1} i_2 U_1 = i_2 U_2$$

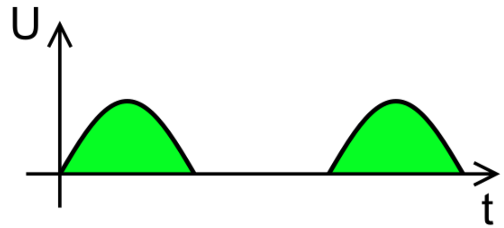
- **If** $i_{10} << \frac{N_2 i_2}{N_1} \quad => \quad i_1 = -\frac{N_2}{N_1} i_2$

Rectifier

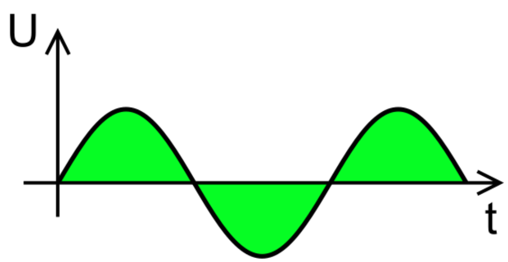
- **Half-wave rectifier:**

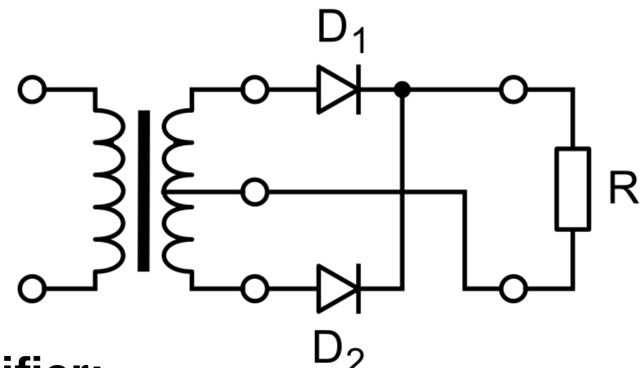


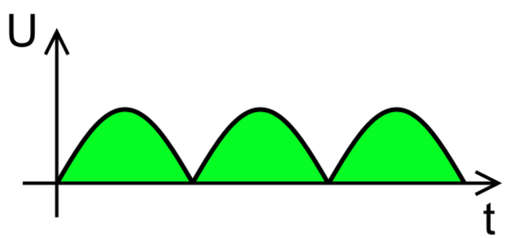




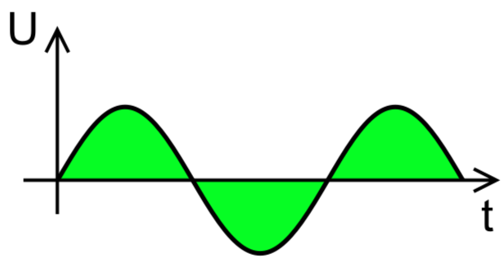
- **Center-tapped full-wave rectifier:**

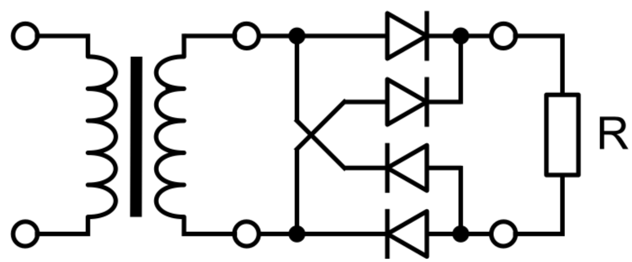


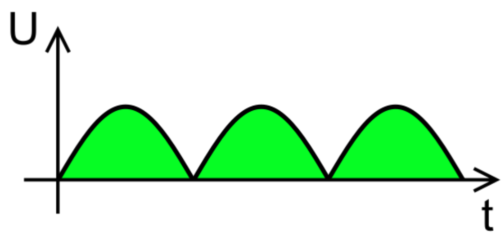




- **Full-wave bridge rectifier:**

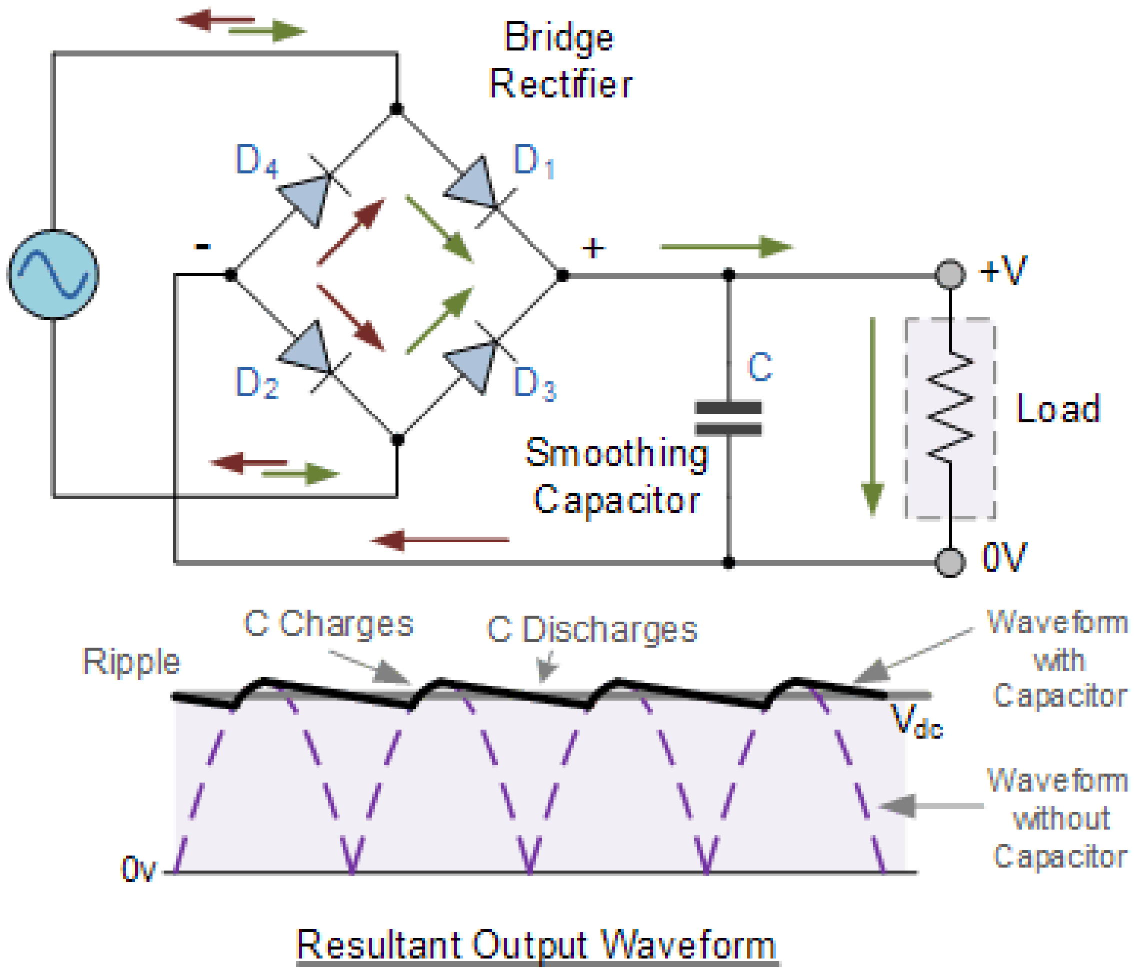






https://zh.wikipedia.org/wiki/%E6%95%B4%E6%B5%81%E5%99%A8

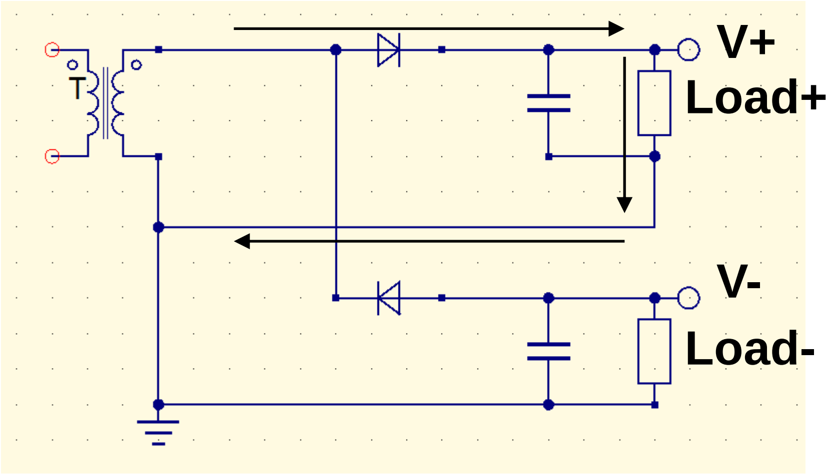
Full-wave rectifier with smoothing capacitor

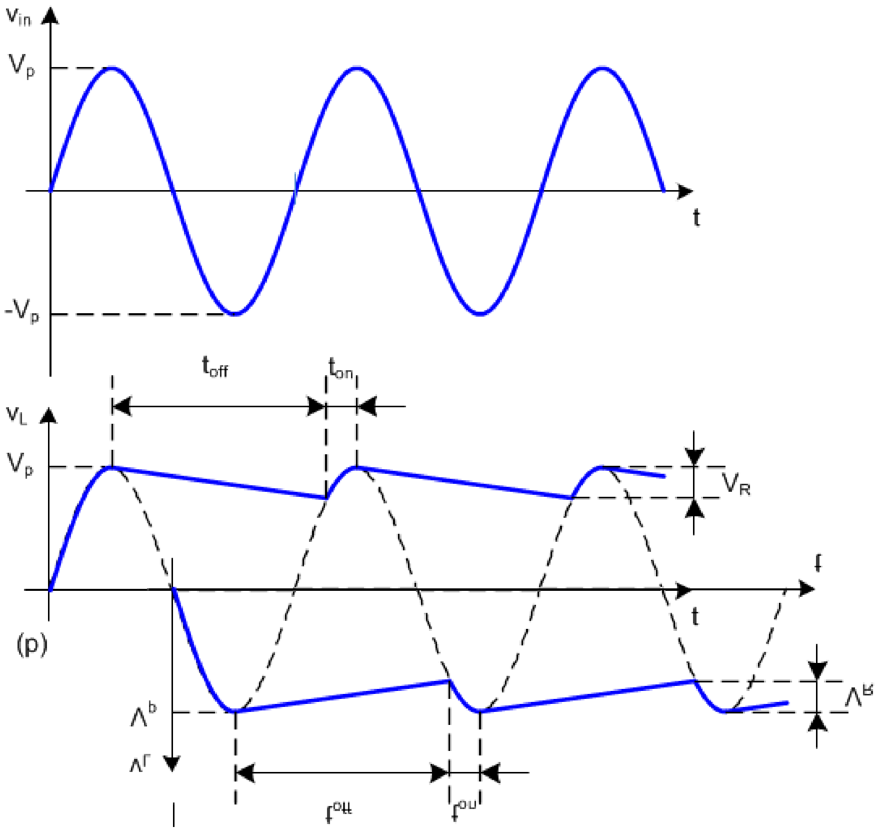


https://electronics.stackexchange.com/questions/363454/smoothing-a-full-wave-rectifier-voltage

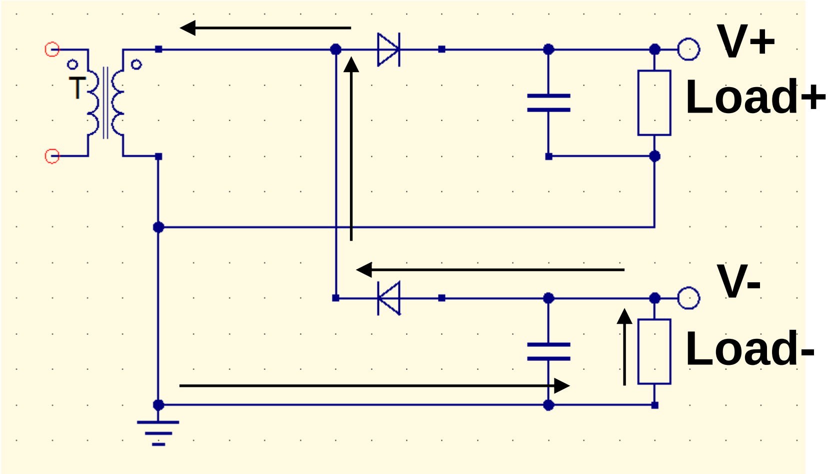
Dual output

- **Positive cycle:**



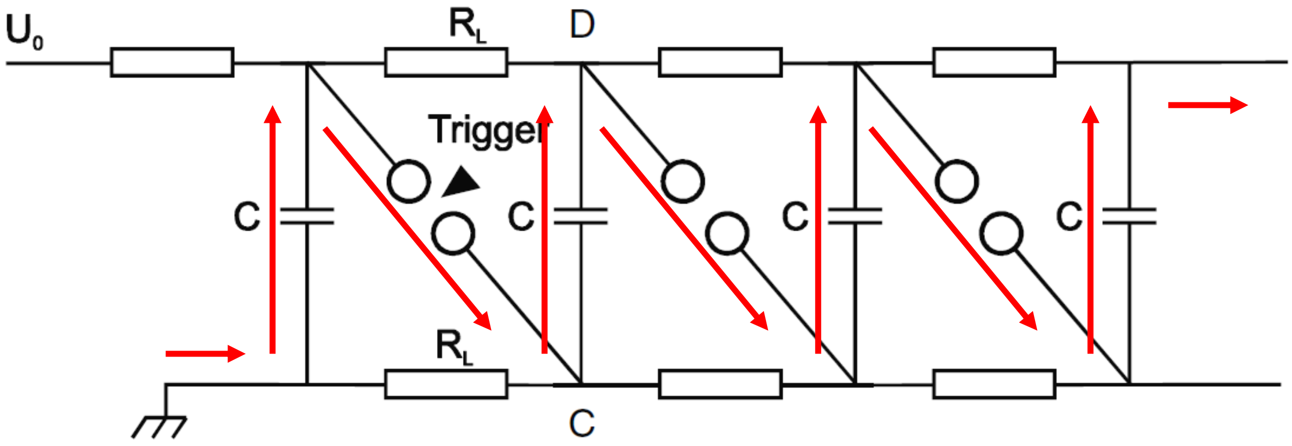


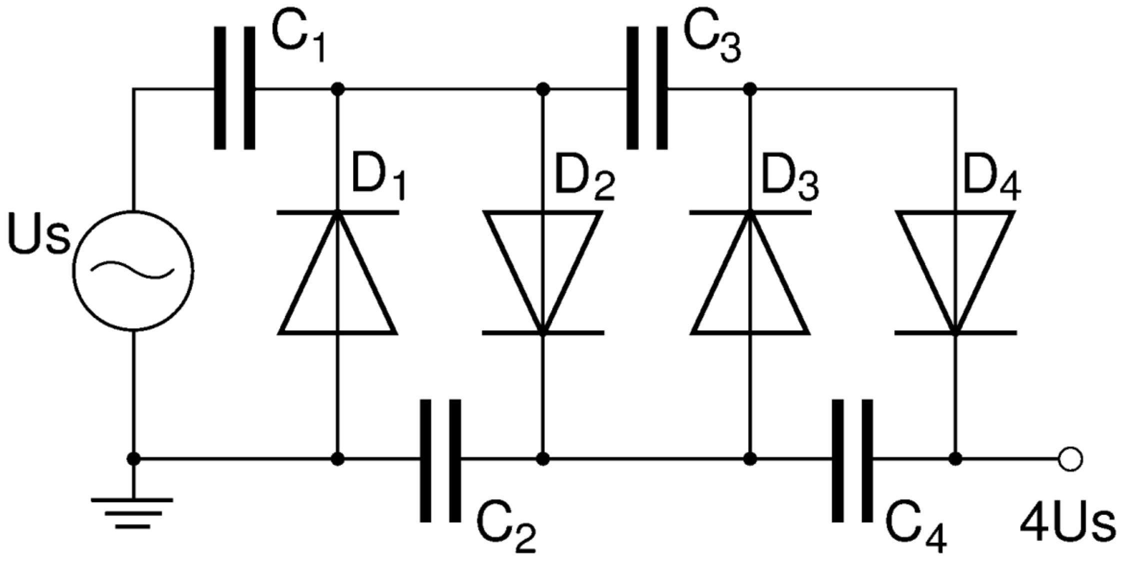
- **Negative cycle:**



http://www.electroniccircuits.be/?page_id=267

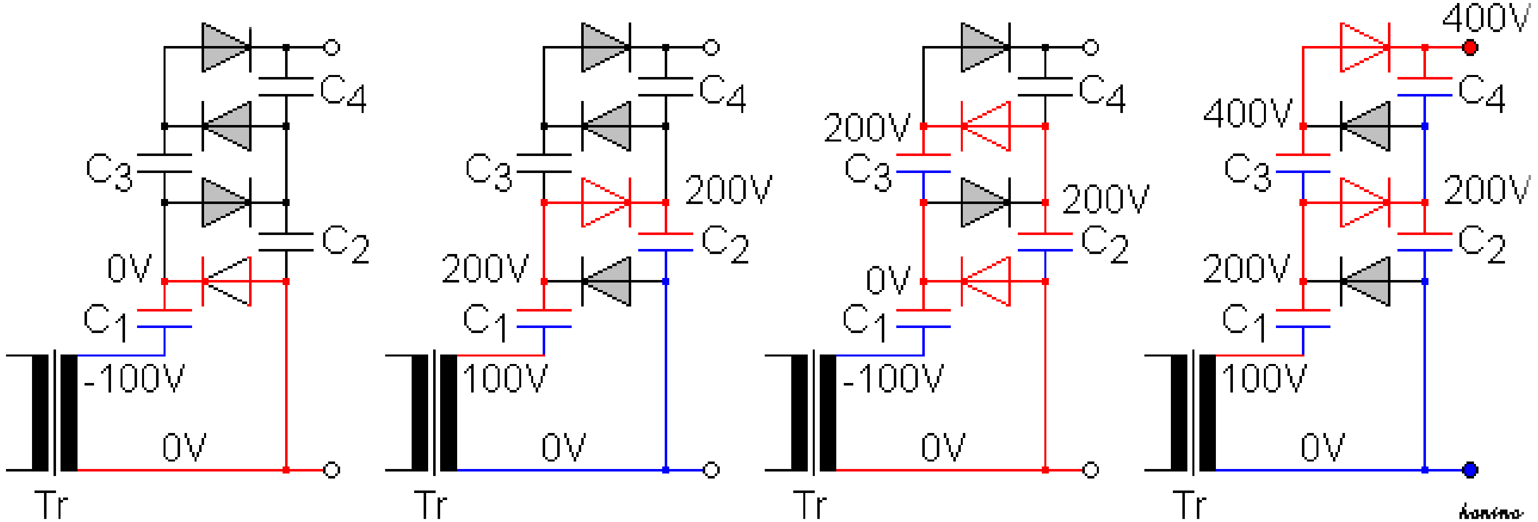
Voltage multiplier (Cockcroft–Walton (CW) generator)

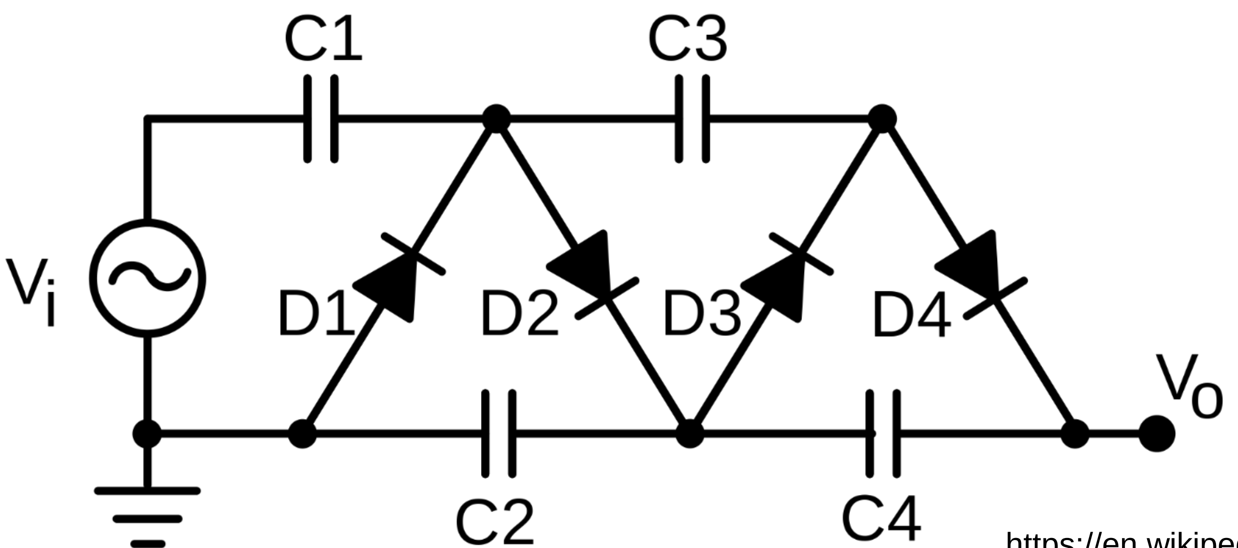




https://en.wikipedia.org/wiki/Voltage_multiplier

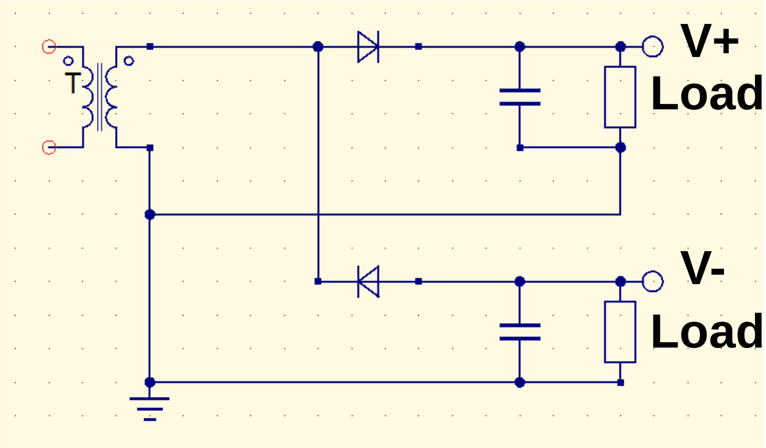
Voltage multiplier (Cockcroft–Walton (CW) generator)

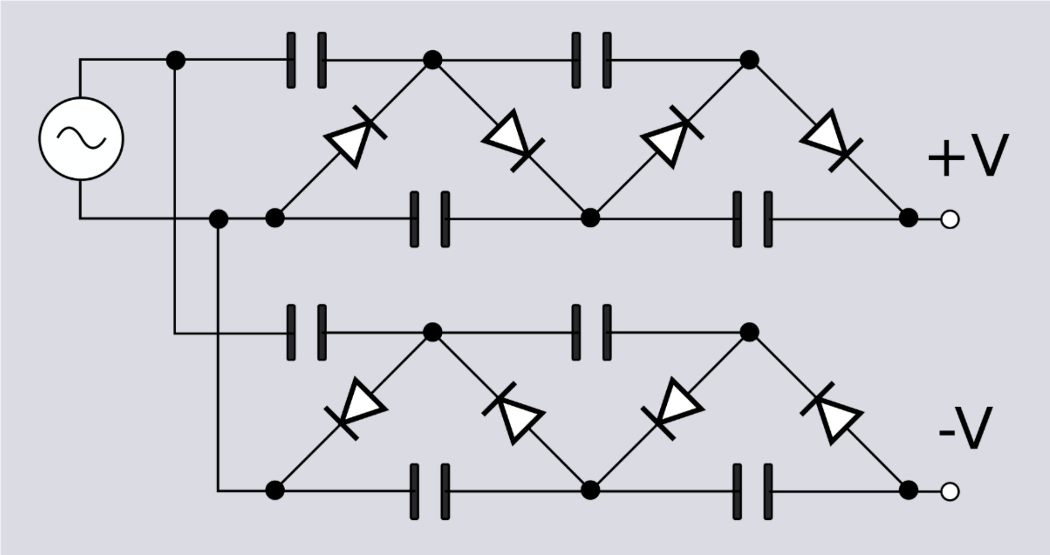




https://en.wikipedia.org/wiki/Voltage_multiplier

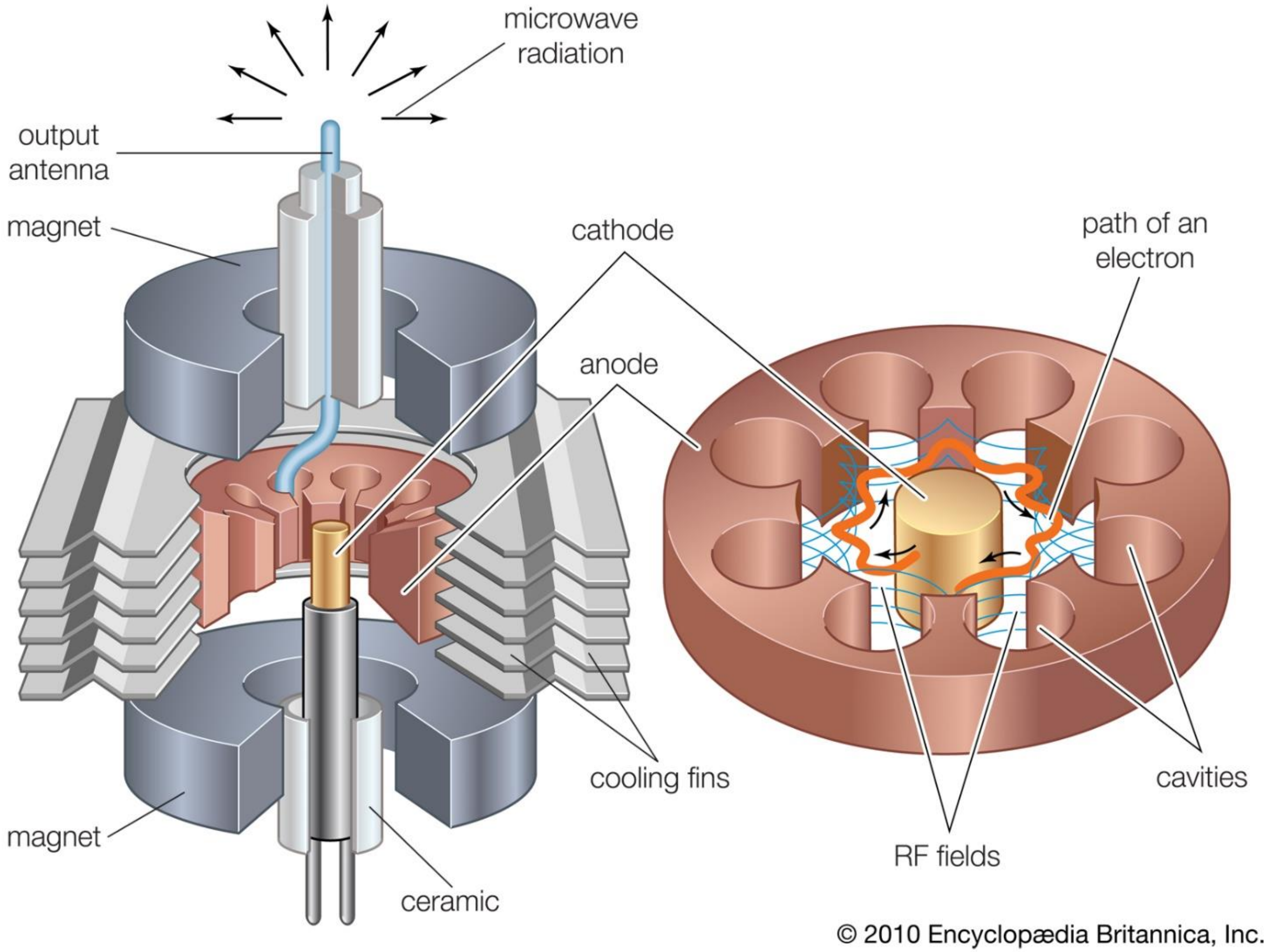
Dual-output





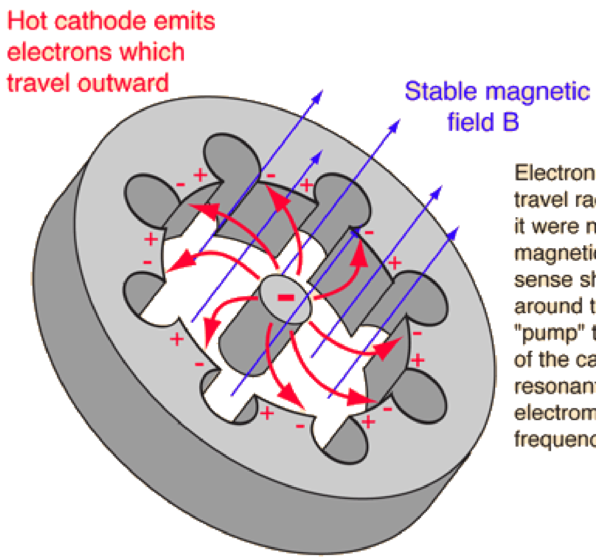
https://en.wikipedia.org/wiki/Voltage_multiplier

Internal of a magnetron



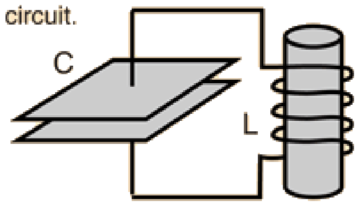
https://kids.britannica.com/students/article/electron-tube/106024/media?assemblyId=137

Magnetron is a forced oscillation driven by electrons between the gap

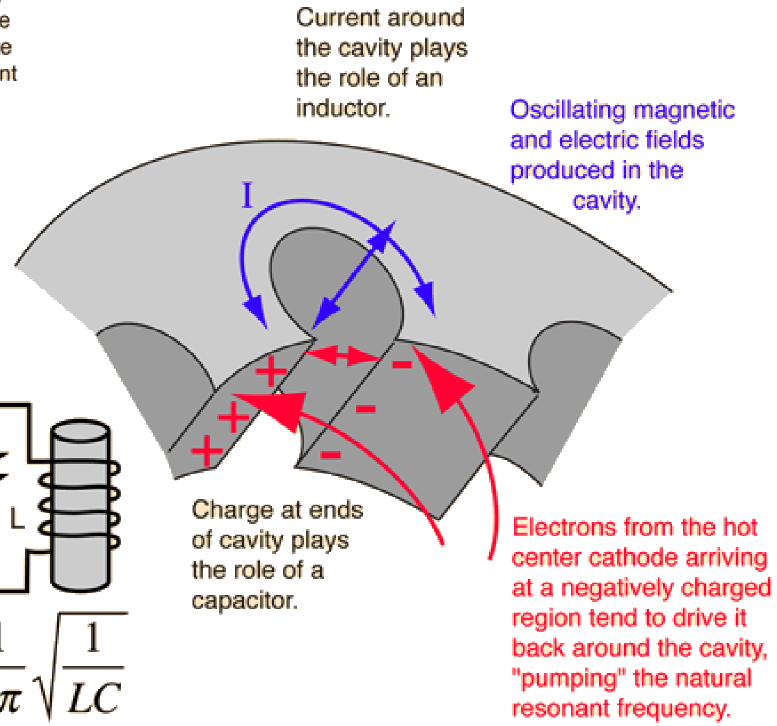


Electrons from a hot filament would travel radially to the outside ring if it were not for the magnetic field. The magnetic force deflects them in the sense shown and they tend to sweep around the circle. In so doing, they "pump" the natural resonant frequency of the cavities. The currents around the resonant cavities cause them to radiate electromagnetic energy at that resonant frequency.

The cavity exhibits a resonance analogous to a parallel resonant circuit.

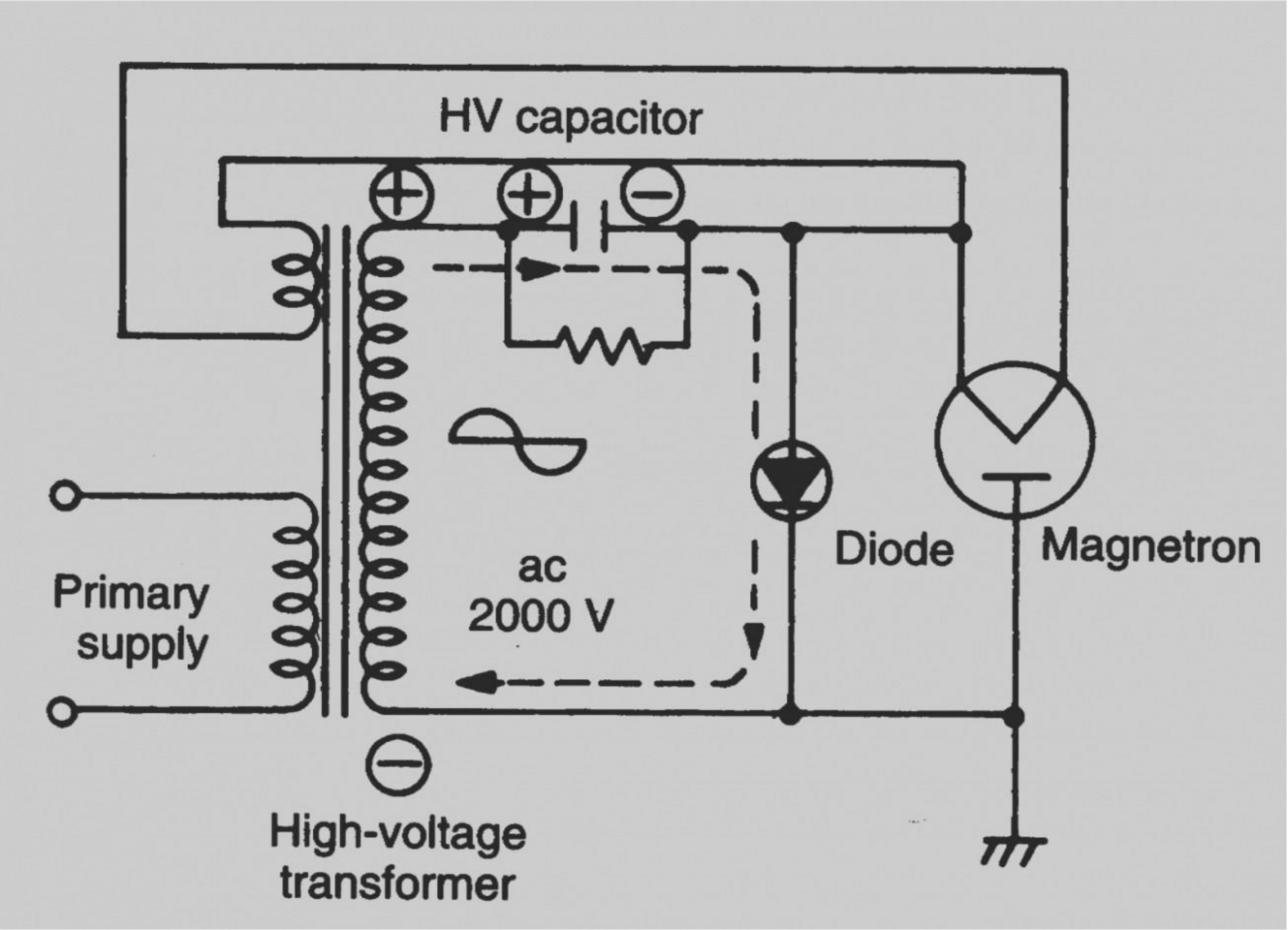


$$f_{resonance} \approx \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$$



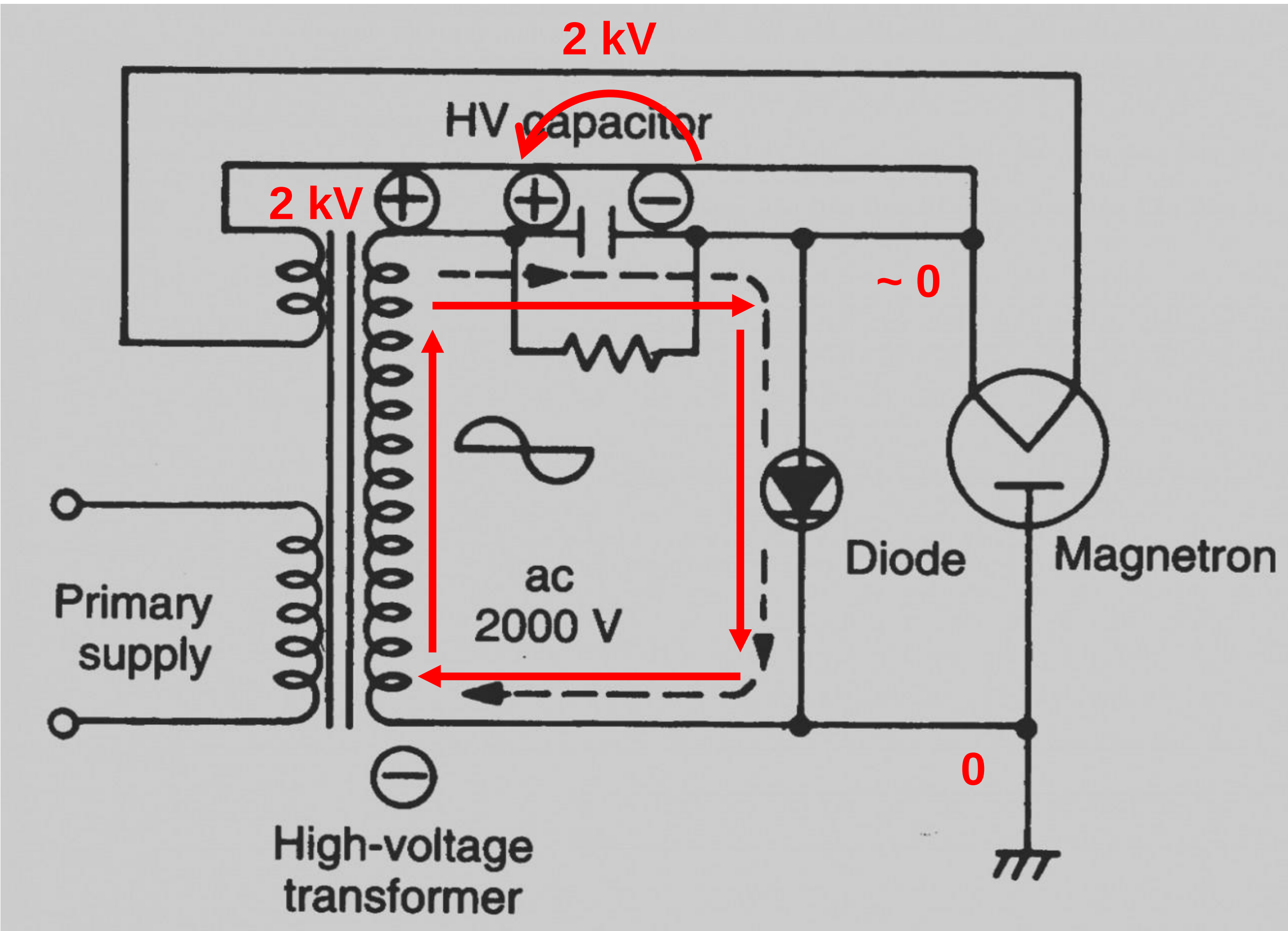
http://hyperphysics.phy-astr.gsu.edu/hbase/Waves/magnetron.html

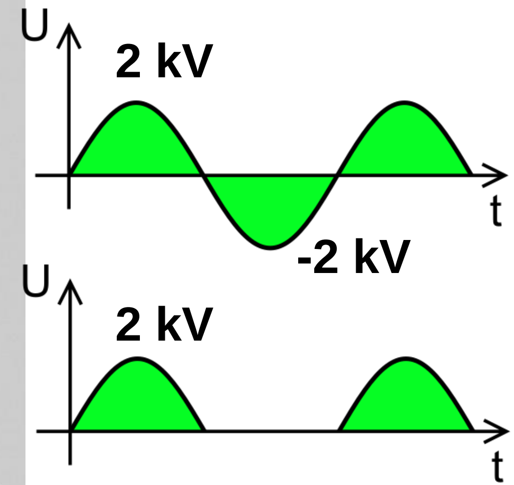
Magnetron schematic diagram



http://www.sciencemadness.org/talk/viewthread.php?tid=154071

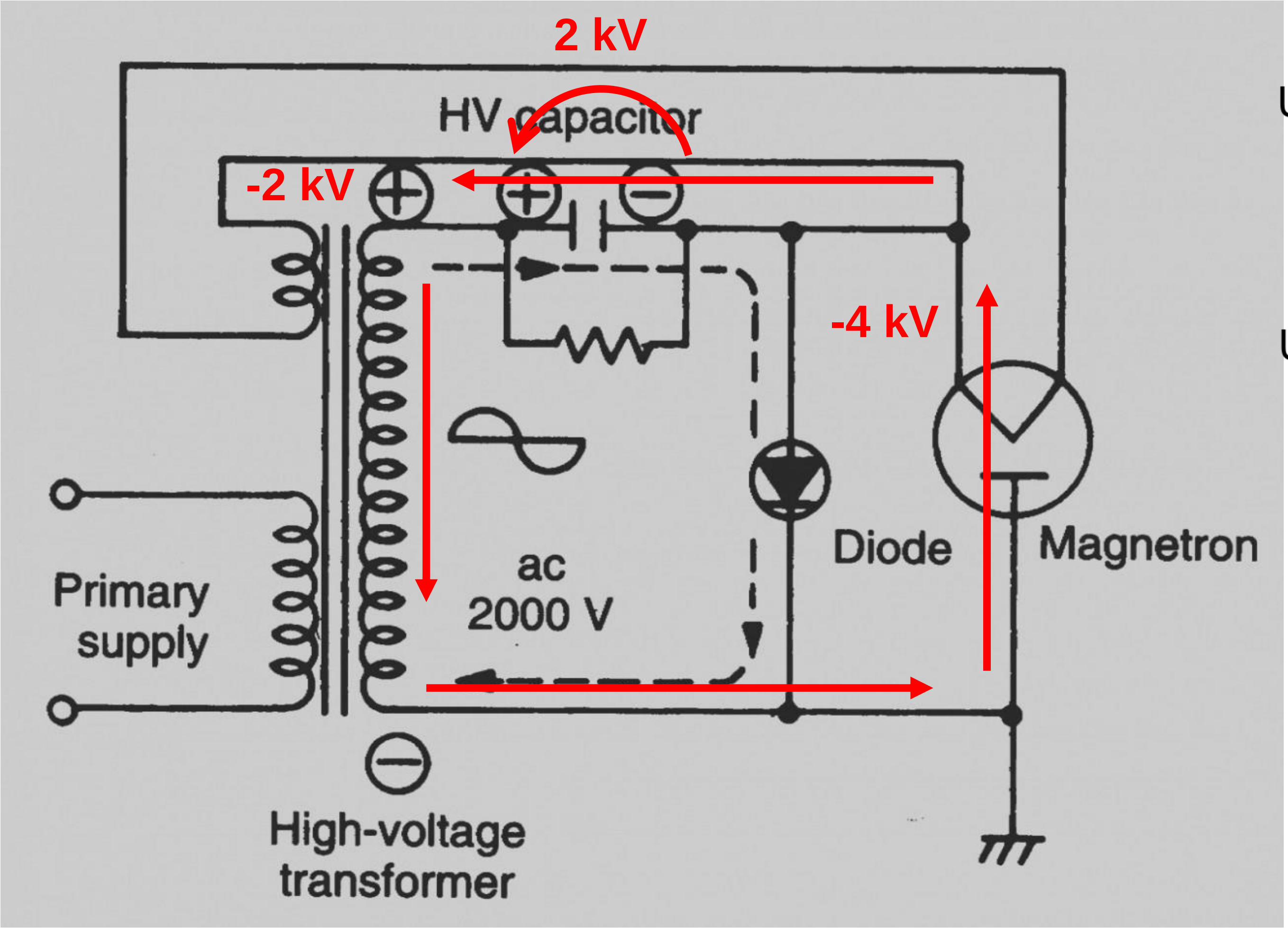
Magnetron schematic diagram

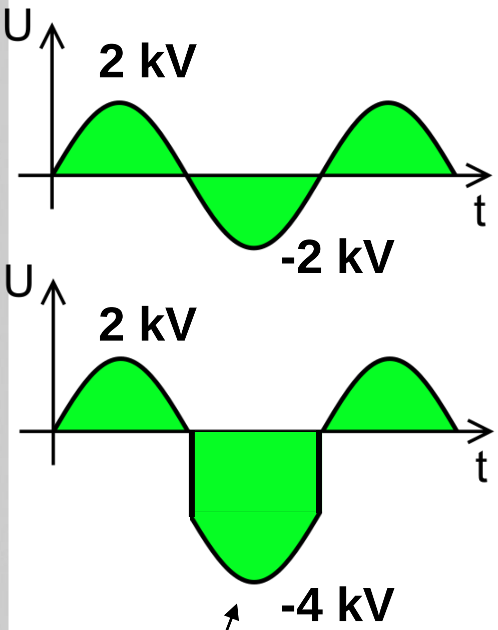




http://www.sciencemadness.org/talk/viewthread.php?tid=154071

Magnetron schematic diagram

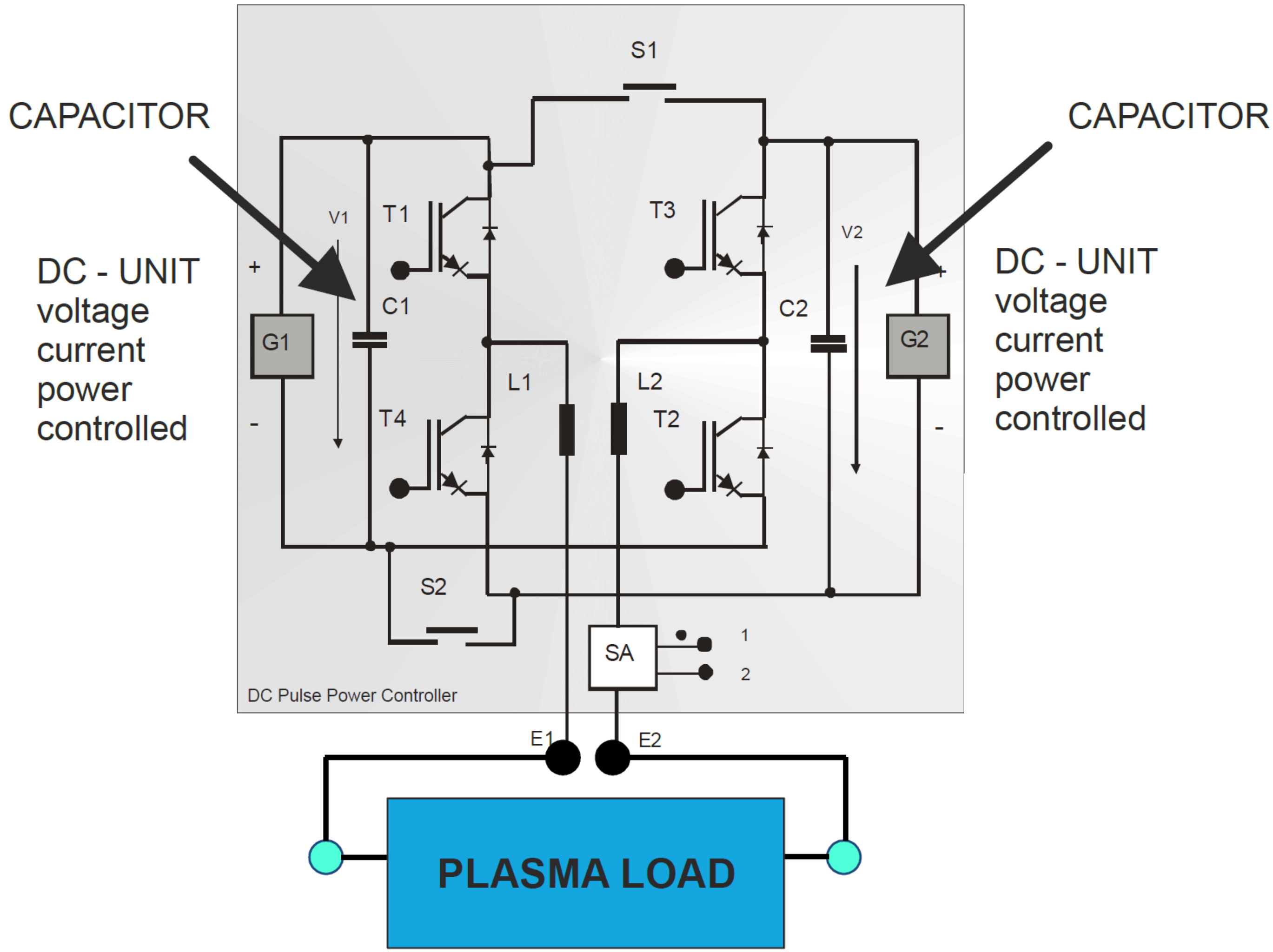




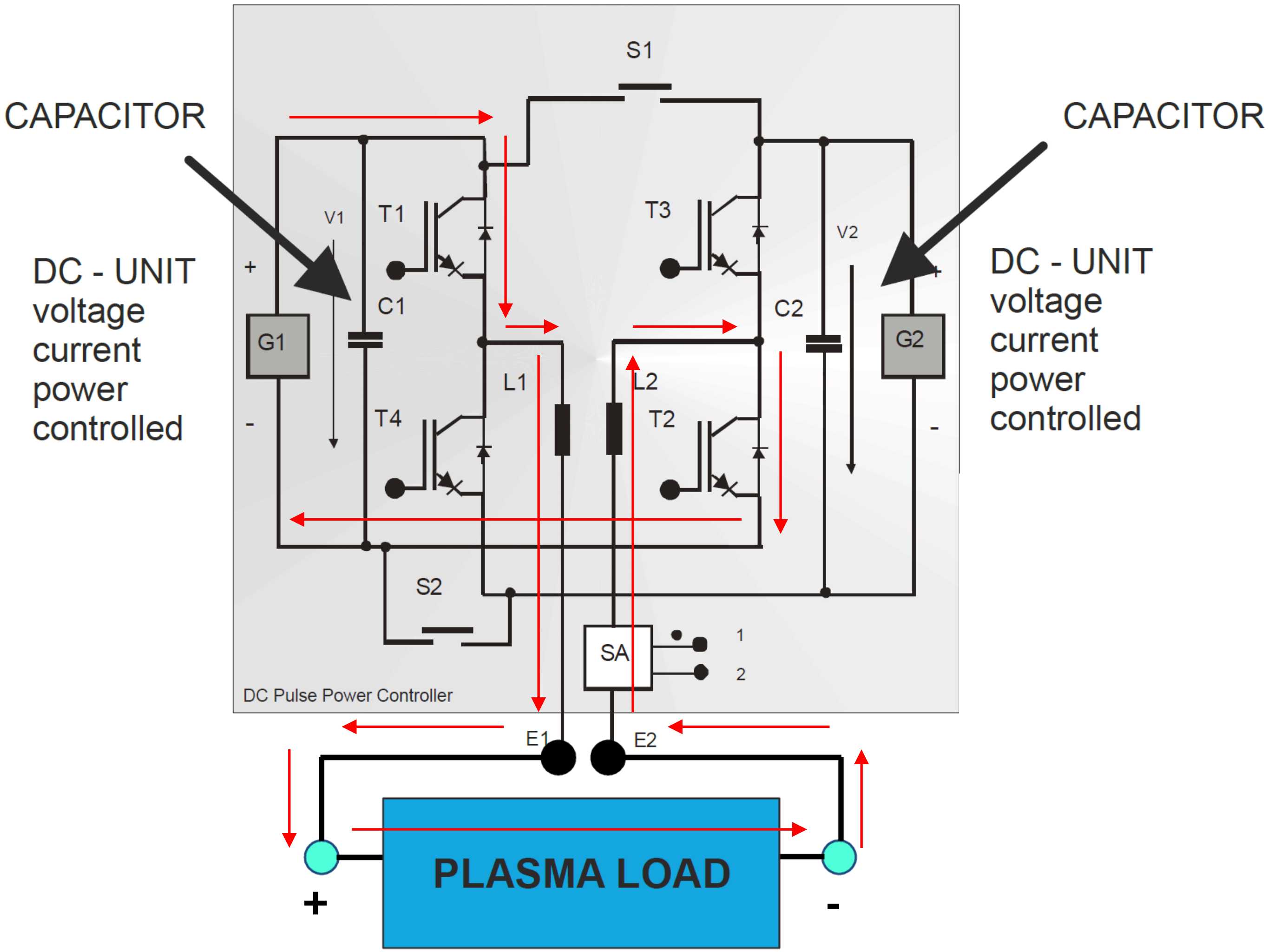
Microwave is generated.

http://www.sciencemadness.org/talk/viewthread.php?tid=154071

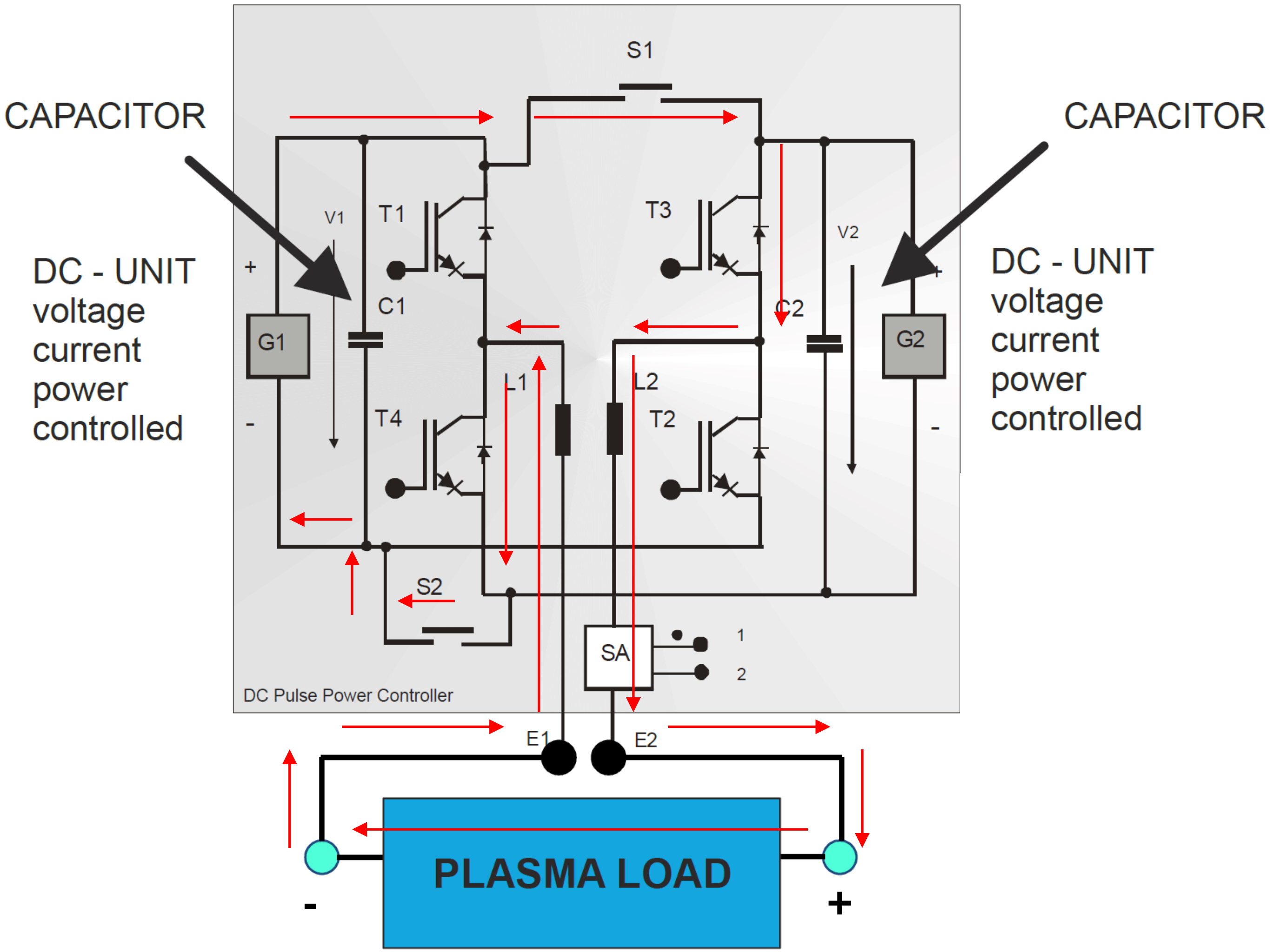
Pulse generator using H-bridge inverter



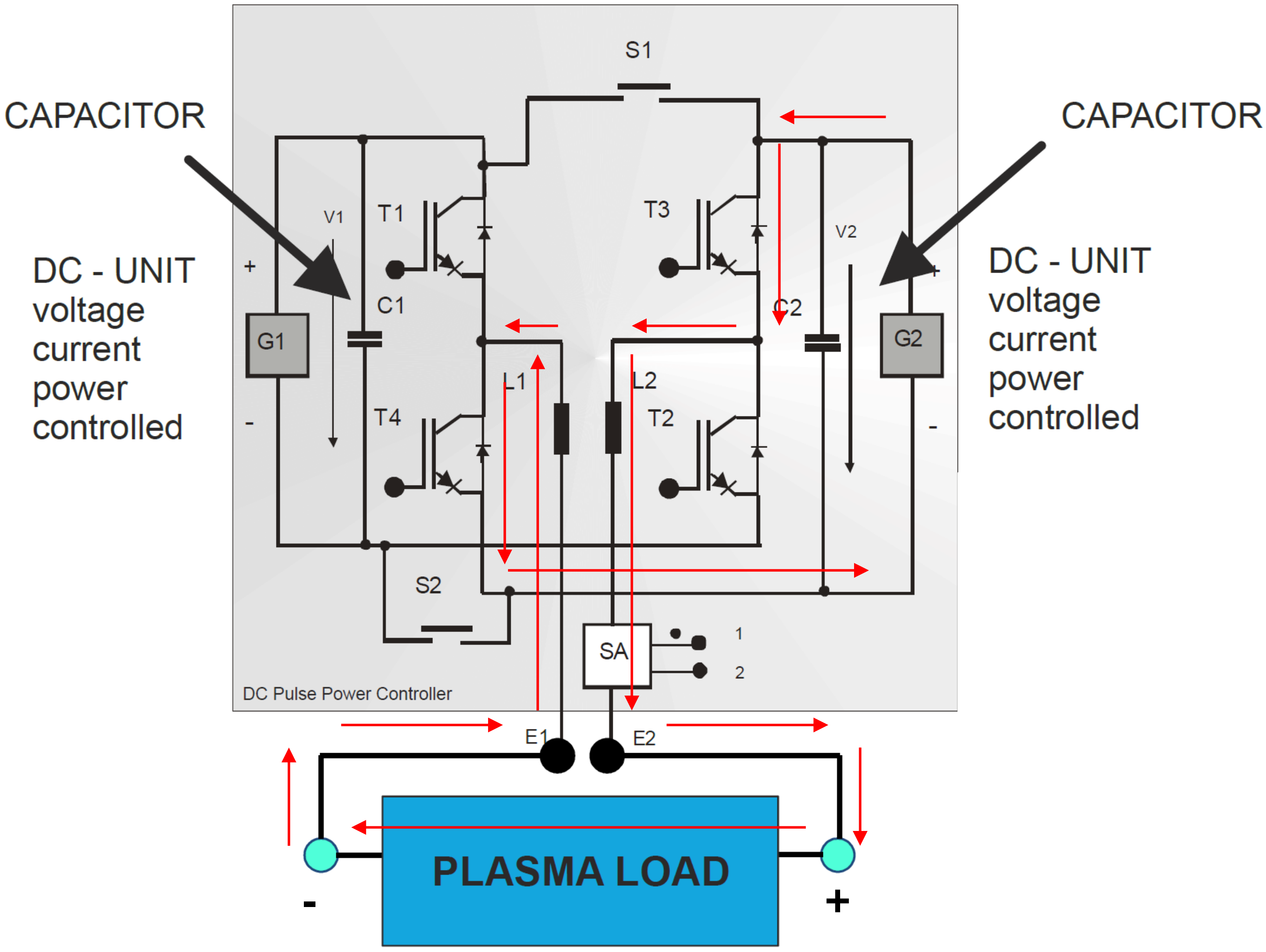
Pulse generator using H-bridge inverter



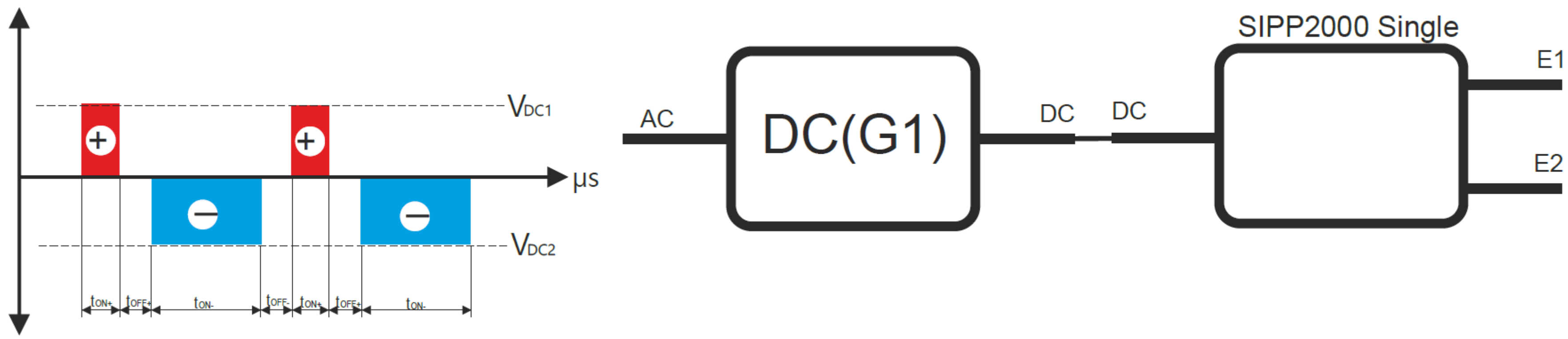
Pulse generator using H-bridge inverter



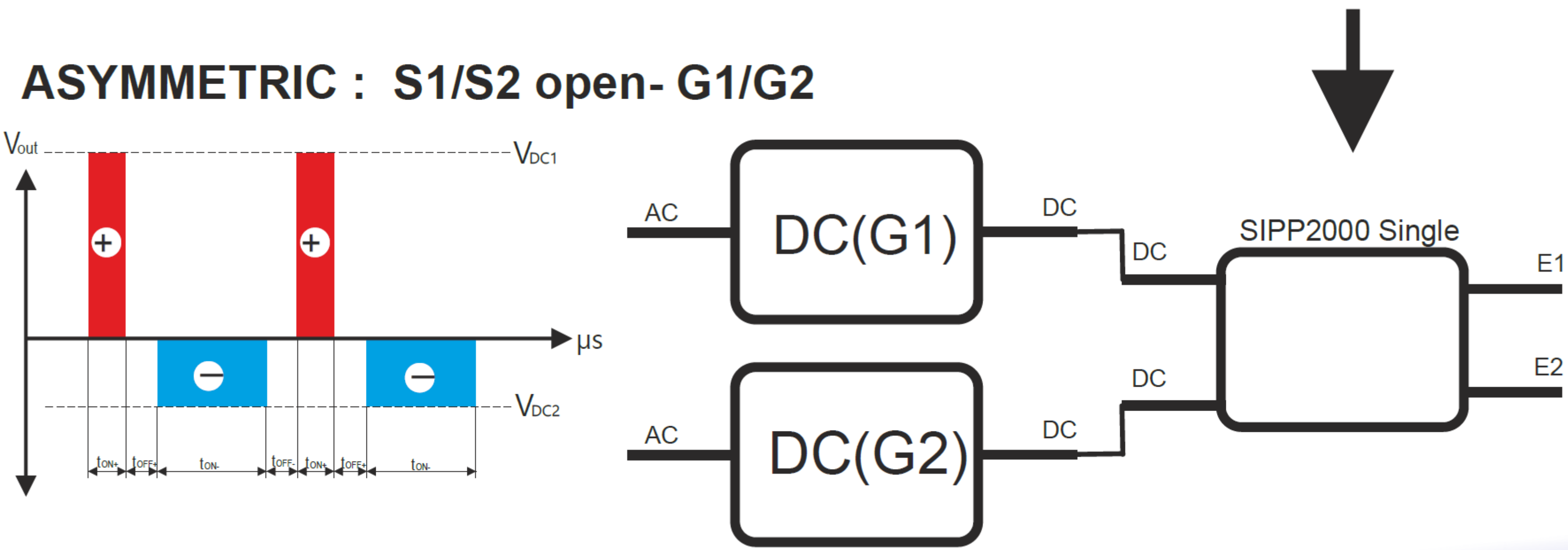
Pulse generator using DC power supply



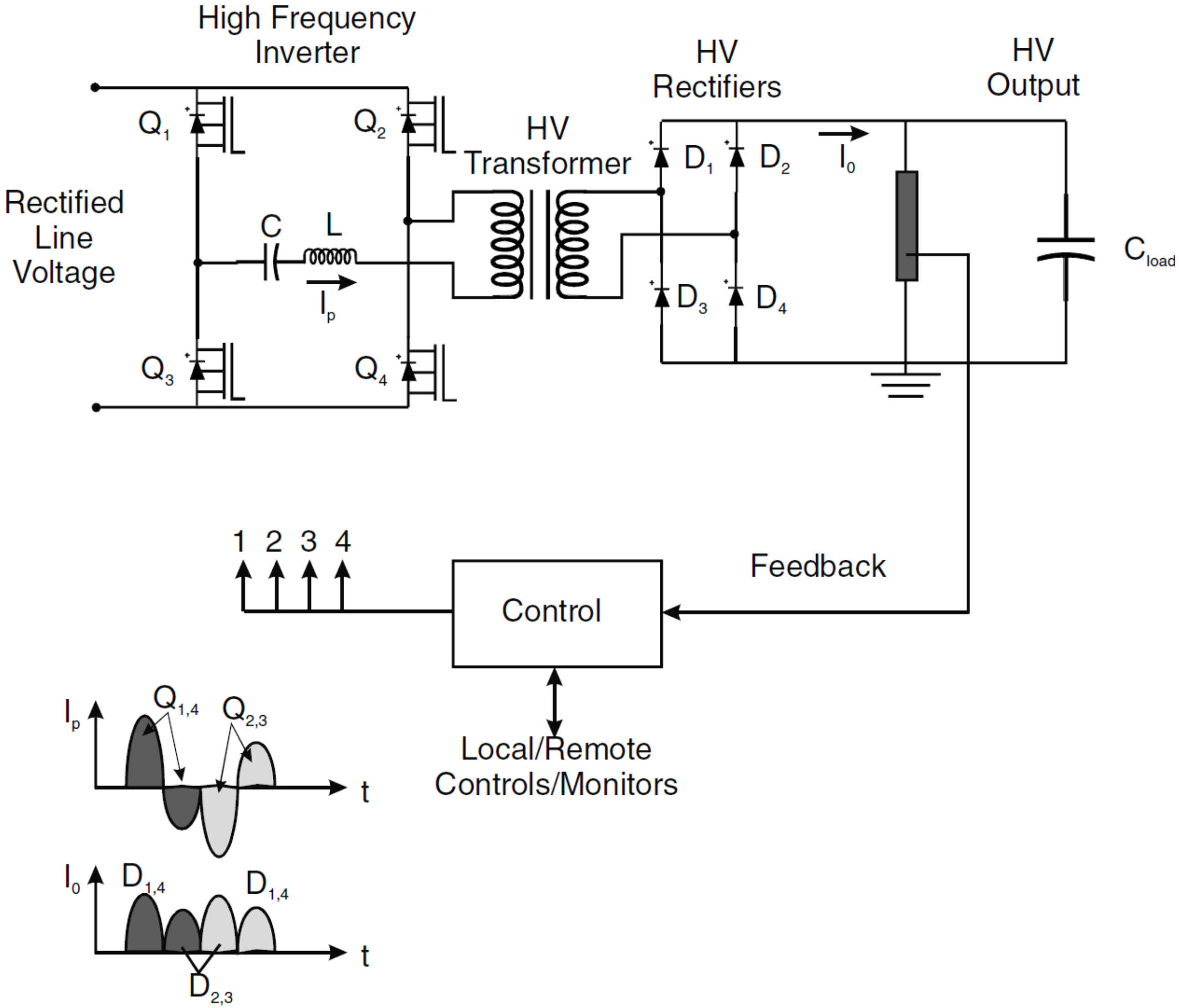
Pulse generator



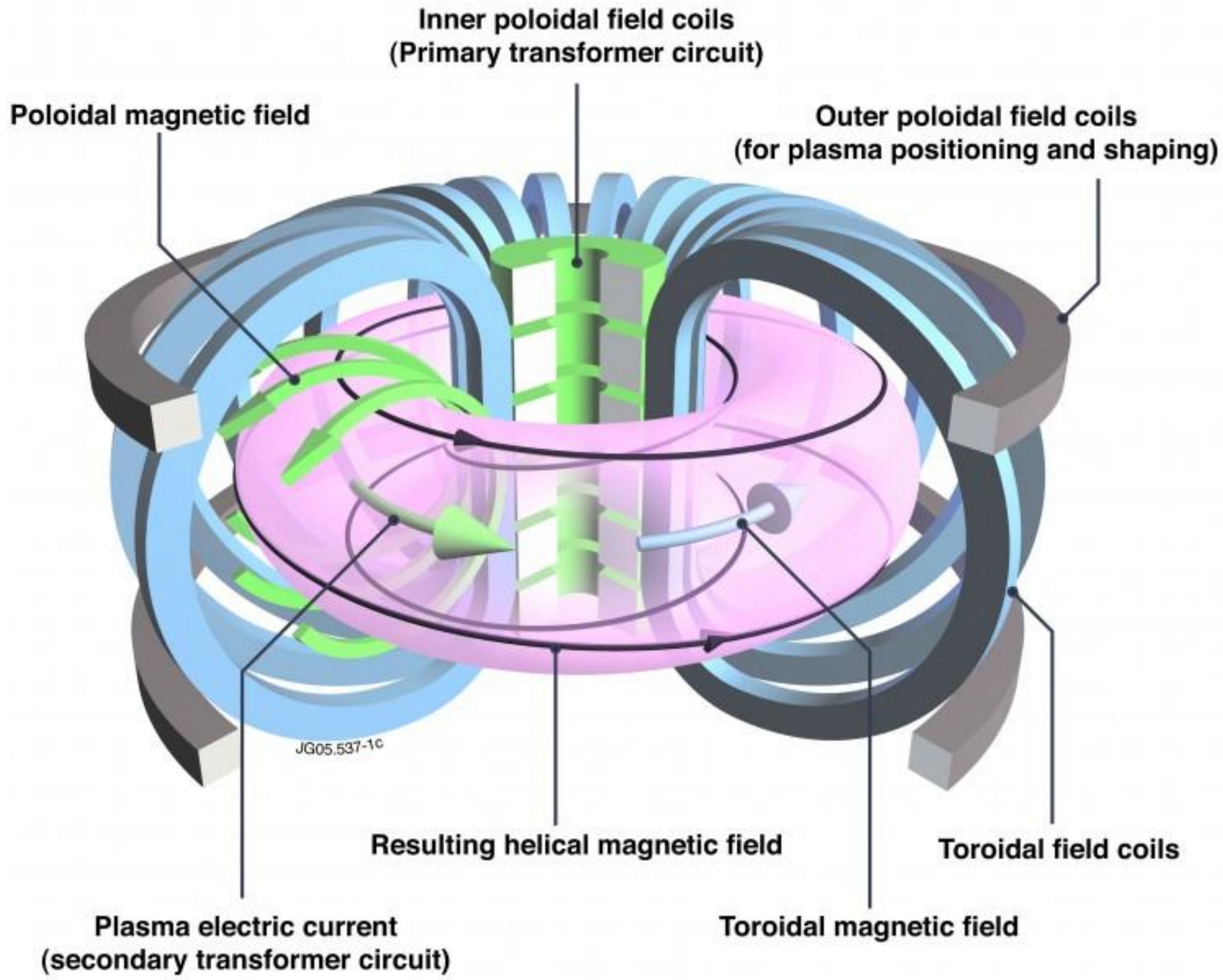
ASYMMETRIC : S1/S2 open- G1/G2



High-frequency switch mode power supply

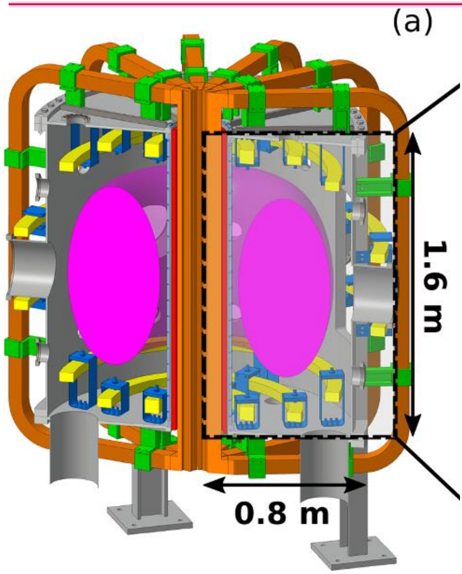


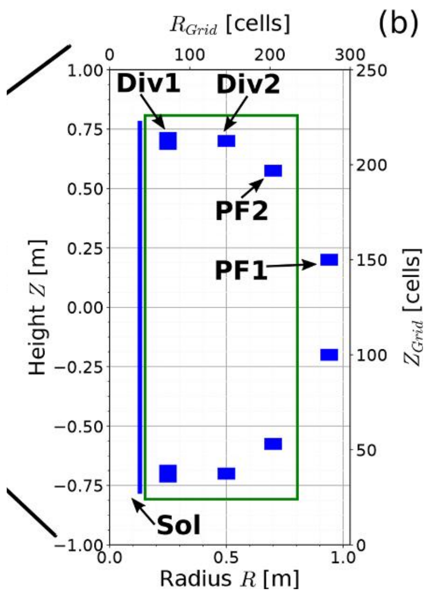
A tokamak is a device to achieve nuclear fusion via confinement plasma using magnetic field



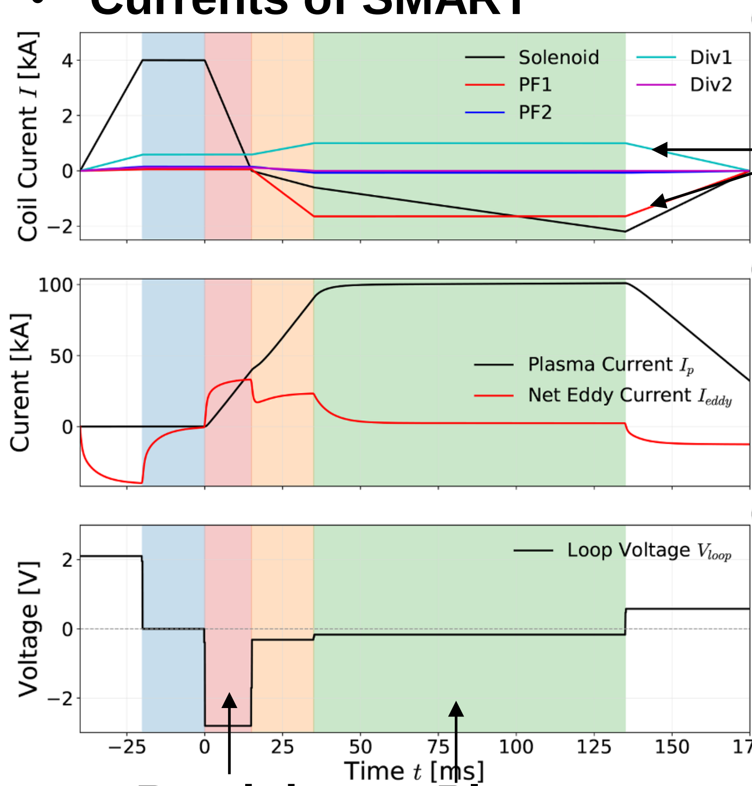
https://www.euro-fusion.org/2011/09/tokamak-principle-2/

Currents with specific profiles needed to be provided to drive coils in Tokamaks to confine the plasma





- **Currents of SMART**



Equilibrium state can be achieved with poloidal field coils.

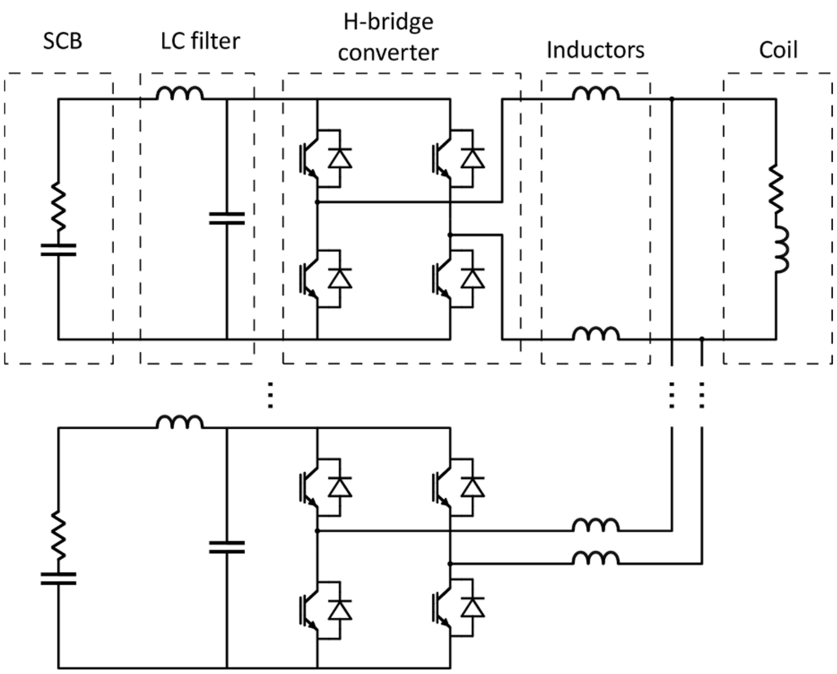
Breakdown **Plasma current is driven.**

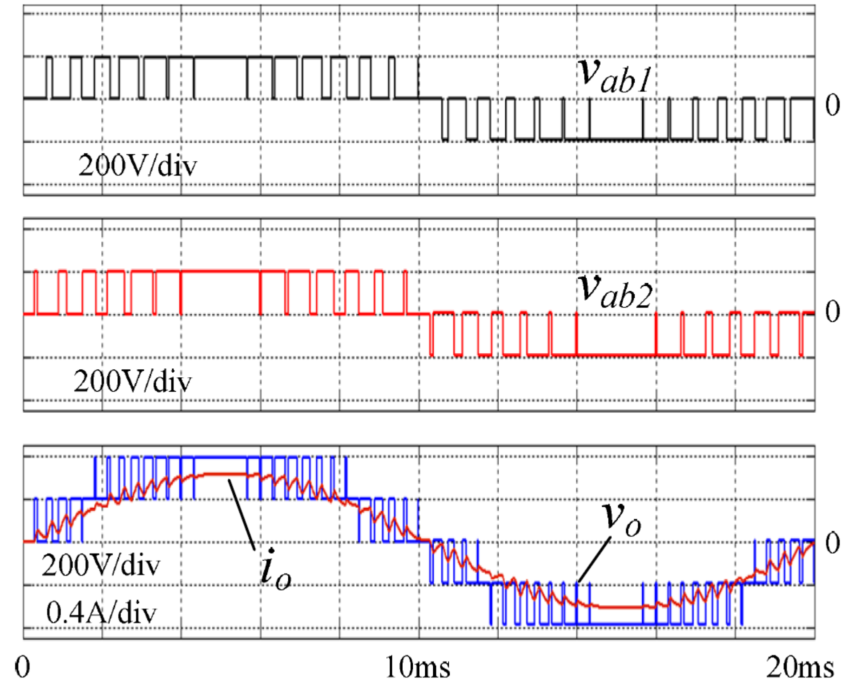
- **The current of the CS will be determined by the required breakdown voltage and plasma current.**

S. J. Doyle, etc., Fusion Eng. Des. **171**, 112706 (2021)

An H-bridge combining pulse width modulation technique will be used to provide the controllable currents

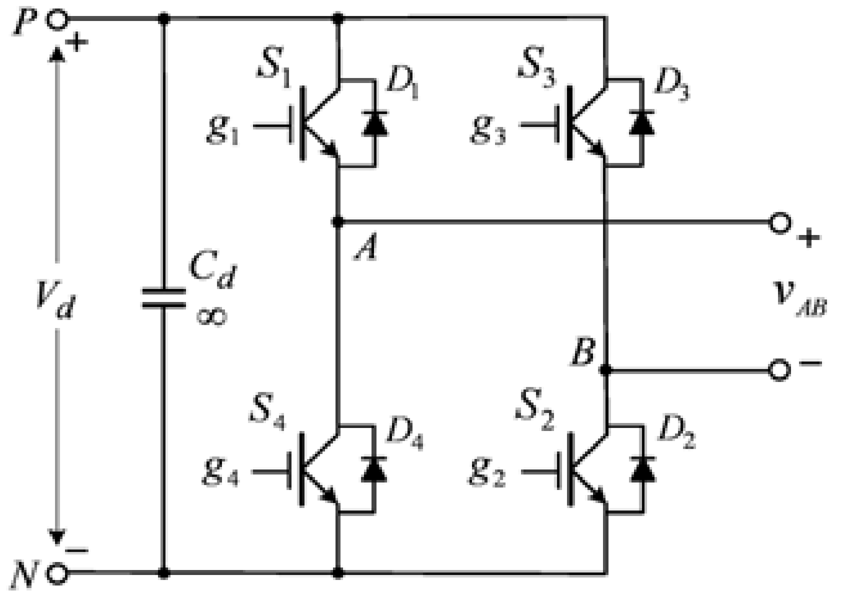
- **H-bridge configuration provides the capability of reversing the current direction:**
- **Pulse width modulation provides the capability of controllable currents**





M. Agredano-Torres, etc., Fusion Eng. Des. **168**, 112683 (2021)
C. Boonmee and Y. Kumsuwan, 2012 15th International Power Electronics and Motion Control Conference, Novi Sad, Serbia, 2012, pp. LS8c.3-1

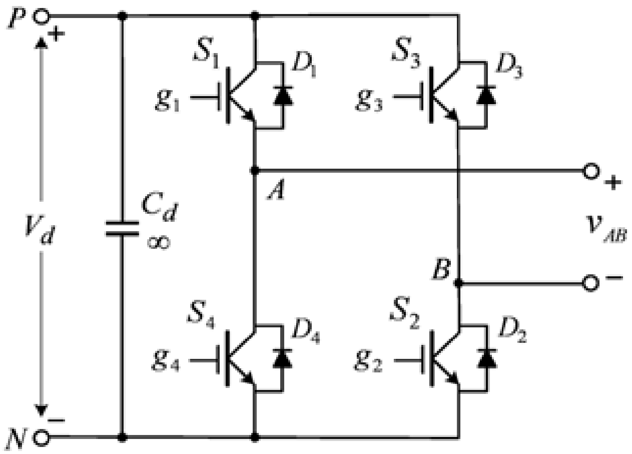
The output voltage is controlled by the status of switches S1~S4

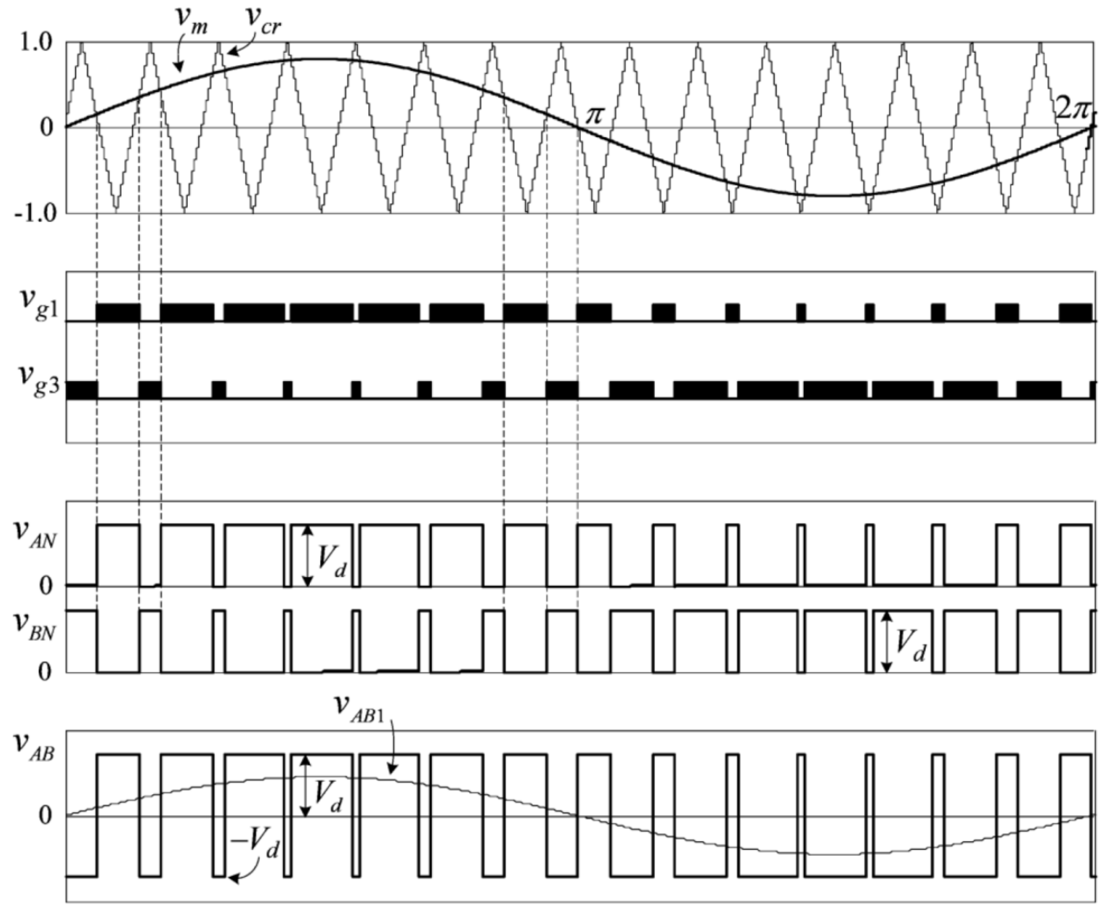


- **S_1/S_2 ON; S_3/S_4 Off: $V_{AB} = V_d$.**
- **S_1/S_2 Off; S_3/S_4 ON: $V_{AB} = -V_d$.**
- **S_1/S_2 ON; S_3/S_4 ON: $V_{AB} = 0$.**

A. Namboodiri & H. S. Wani, I. J. Innovative Research in Sci. & Tech. 1, 2349 (2014)

Bipolar Modulation Scheme

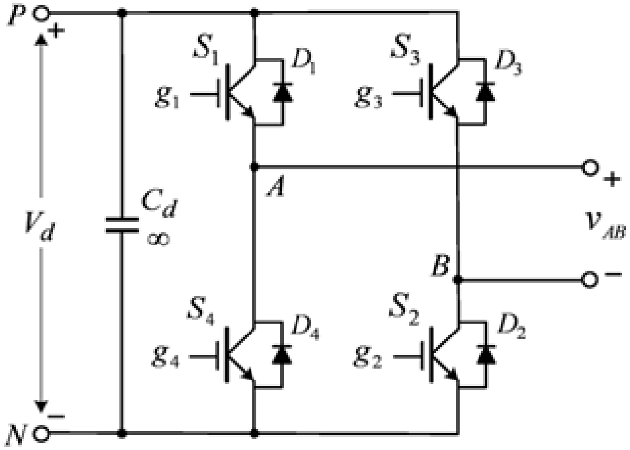


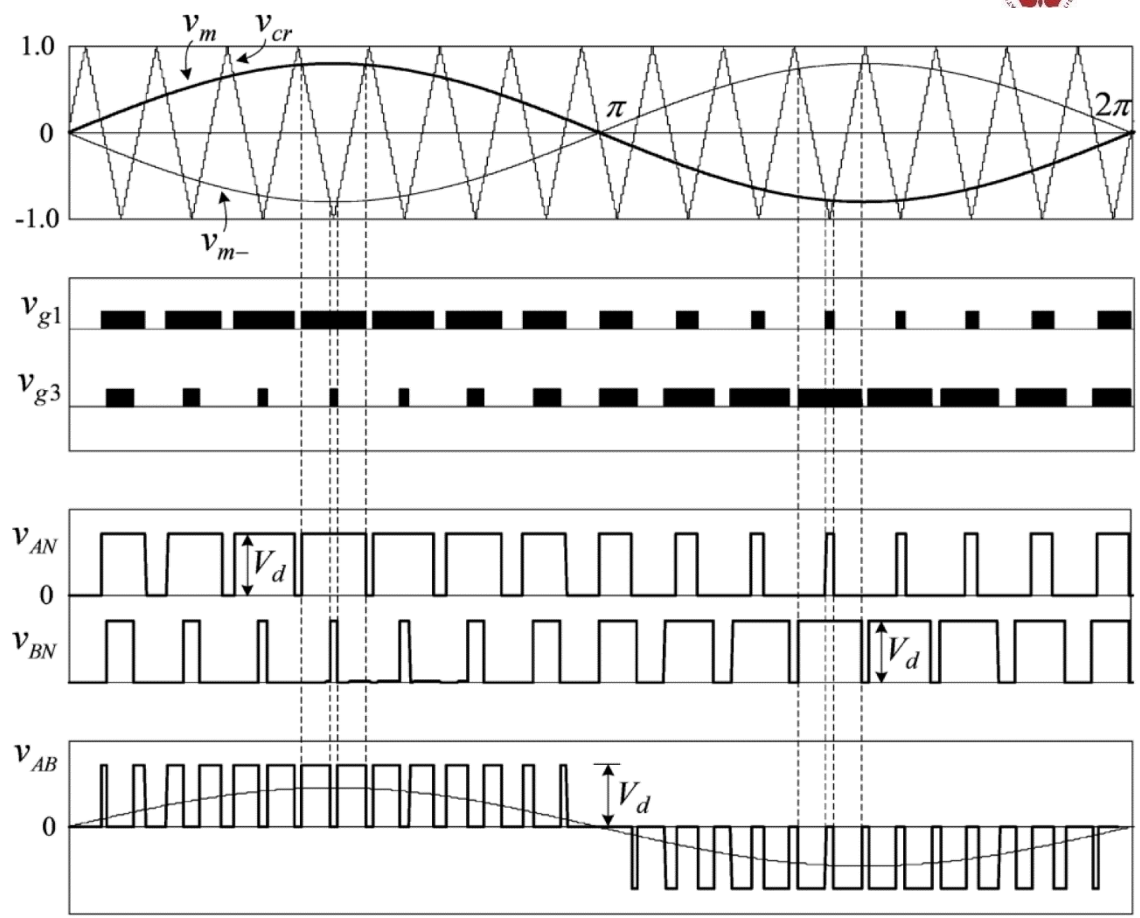


- S_1/S_2 ON; S_3/S_4 Off: $V_{AB} = V_d$.
- S_1/S_2 Off; S_3/S_4 ON: $V_{AB} = -V_d$.
- S_1/S_2 ON; S_3/S_4 ON: $V_{AB} = 0$.

A. Namboodiri & H. S. Wani, I. J. Innovative Research in Sci. & Tech. 1, 2349 (2014)

Unipolar Modulation Scheme

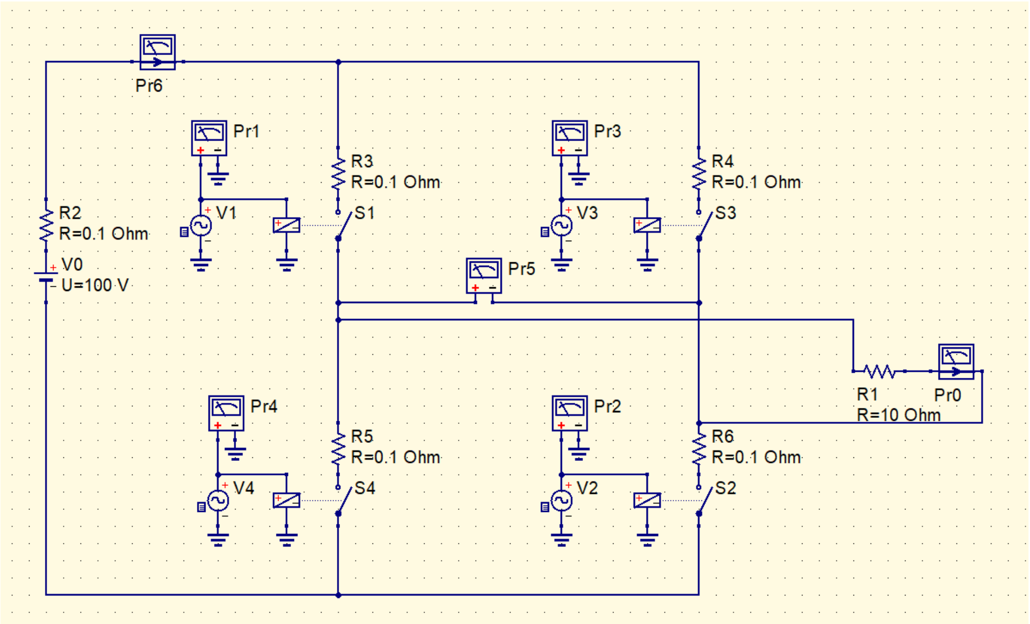


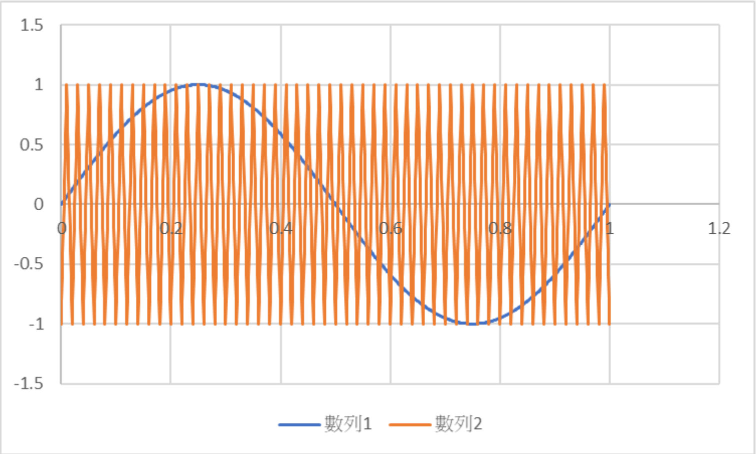


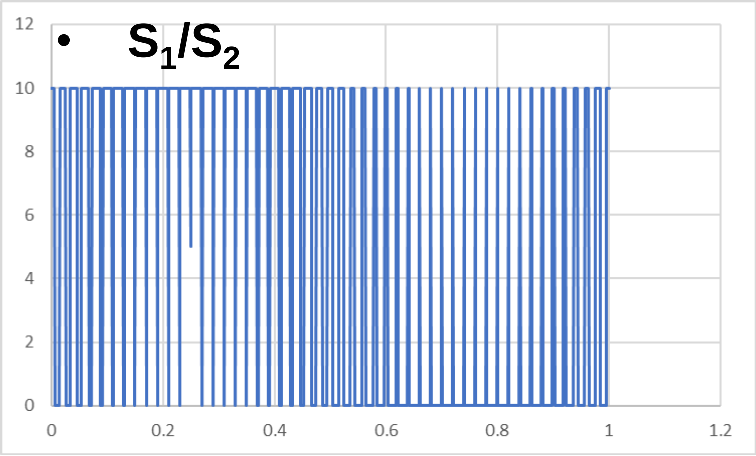
- S_1/S_2 ON; S_3/S_4 Off: $V_{AB} = V_d$.
- S_1/S_2 Off; S_3/S_4 ON: $V_{AB} = -V_d$.
- S_1/S_2 ON; S_3/S_4 ON: $V_{AB} = 0$.

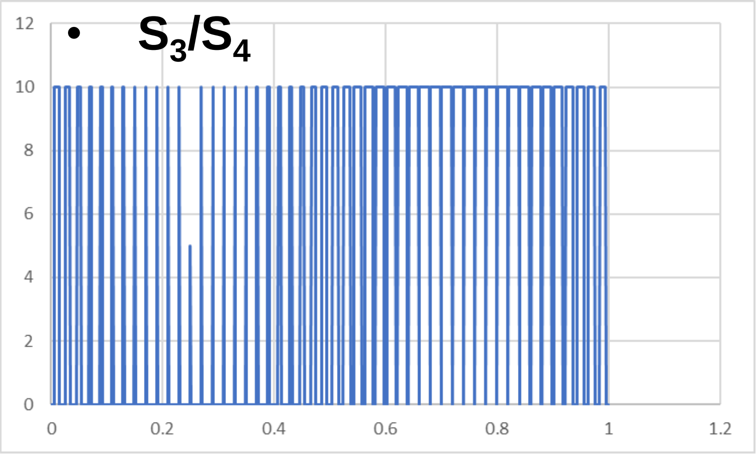
A. Namboodiri & H. S. Wani, I. J. Innovative Research in Sci. & Tech. 1, 2349 (2014)

Simulation using bipolar modulation scheme

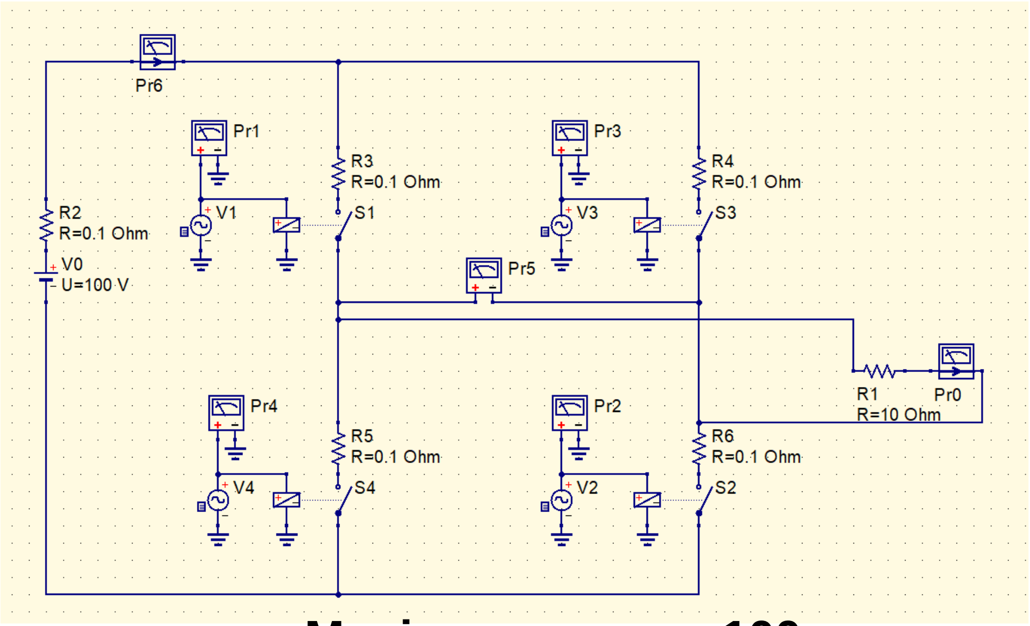




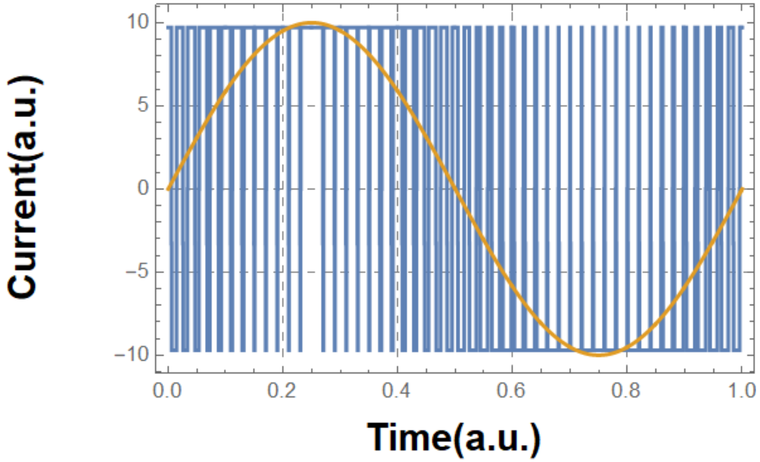




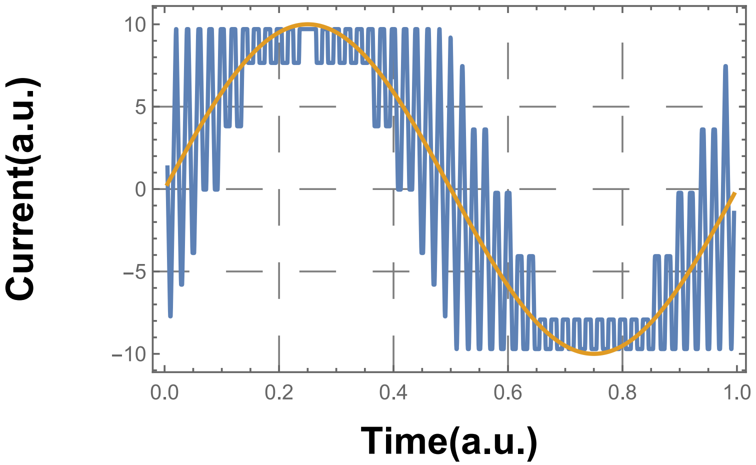
Simulation using bipolar modulation scheme



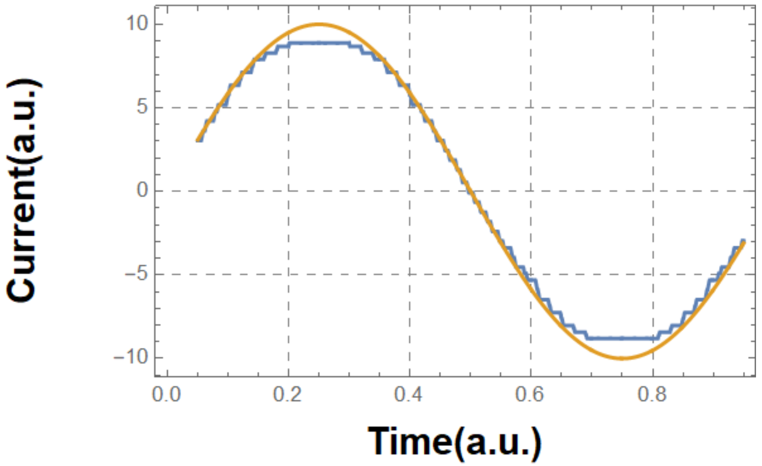
- **Raw data**



- **Moving average = 100**



- **Moving average = 1000**



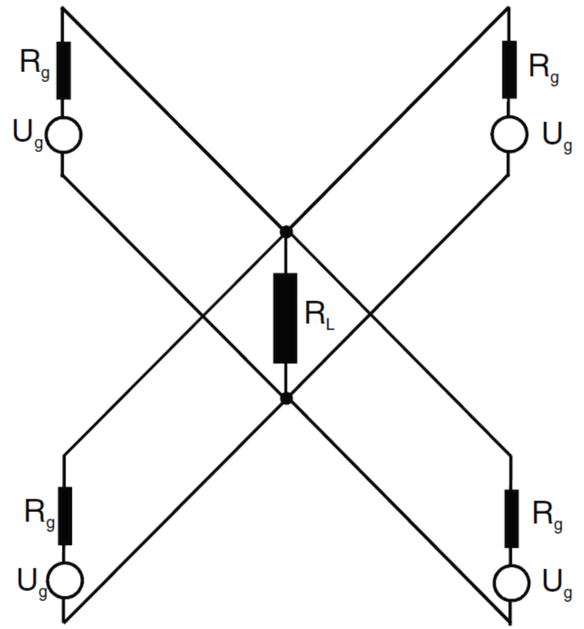
Outlines

- **Power and voltage adding**
  - **Marx generator**
  - **LC generator**
  - **Line pulse transformers**
  - **Induction voltage adder (IVA)**
  - **Linear induction accelerator (LIA)**
  - **Linear transformer driver (LTD)**
- **Diagnostics**
  - **Voltage measurement**
  - **Current measurement**
- **Applications of pulsed-power system**

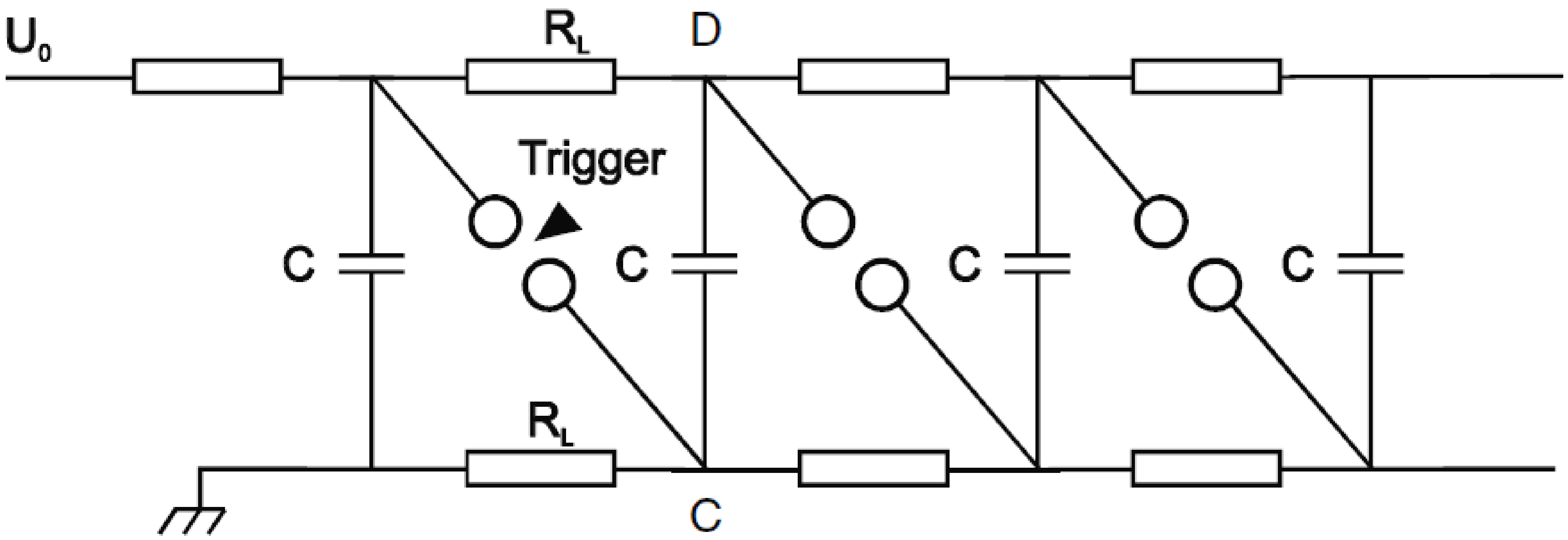
Power and voltage adding

- For pulsed-power levels become very high (≧15 TW), the generator must be divided into separately units, which can be constructed much more compactly and thus use the available volume much more efficiently.
- Synchronizing independent lines requires special measures, e.g., laser-triggered switches with very low jitter.
- Match load needed:

$$R_L = \frac{R_g}{n}$$

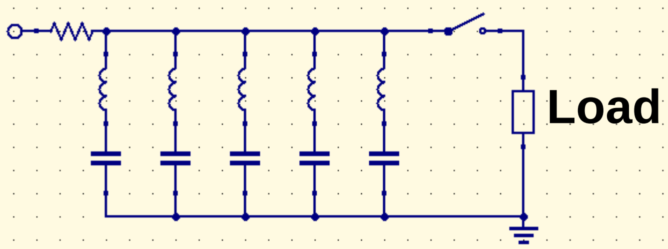


Marx generator

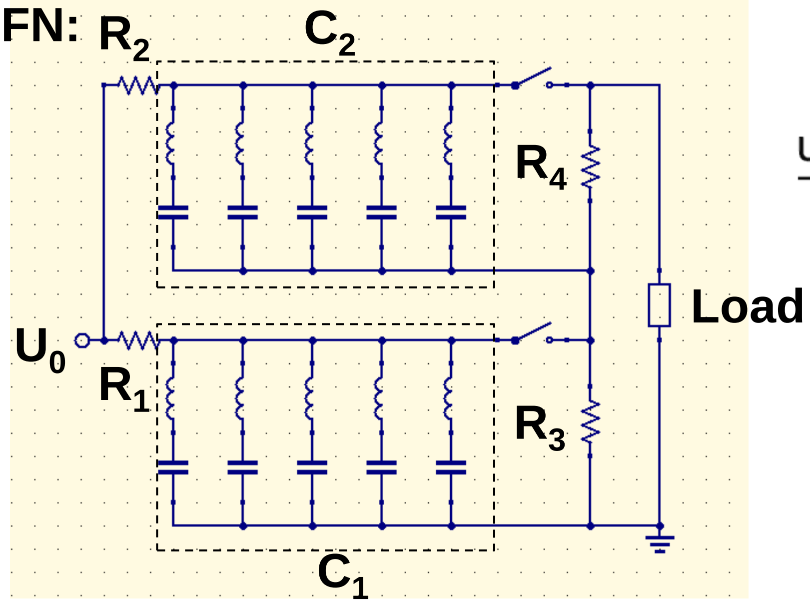


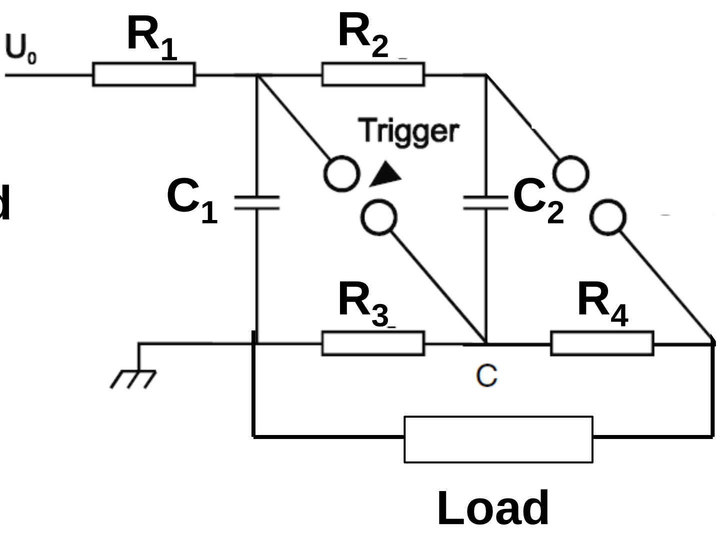
PFN-Marx

- **PFN:**



- **2-stage PFN:**

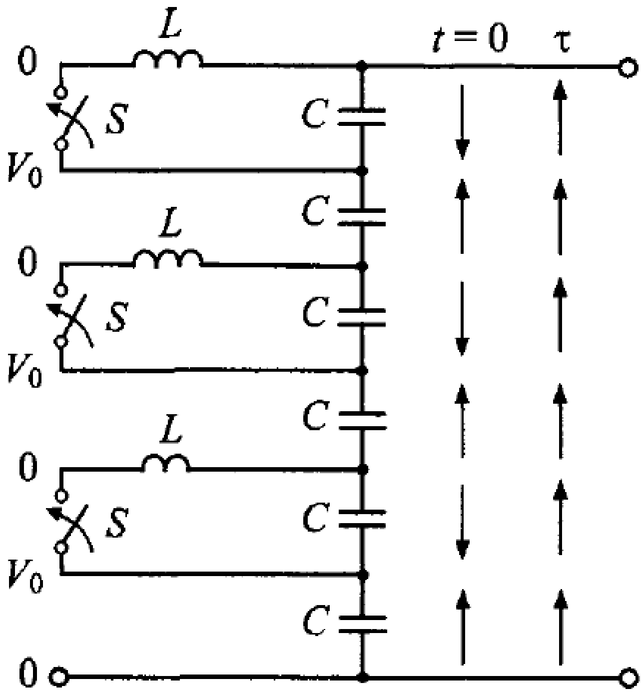




LC generator

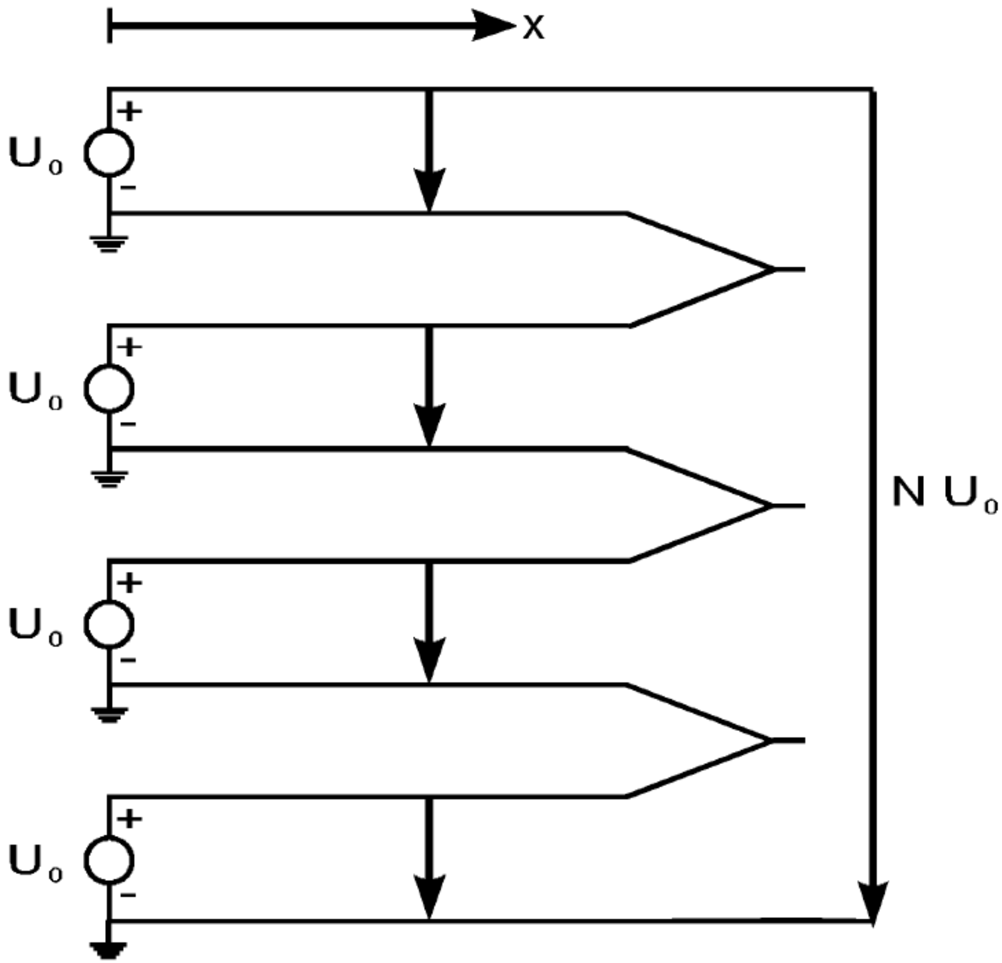
$$t = \tau = \pi\sqrt{LC} \quad V_{out} = NV_0$$

$$V_{out}(t) = NV_0[1 - e^{\alpha t}\cos(\omega t)]$$

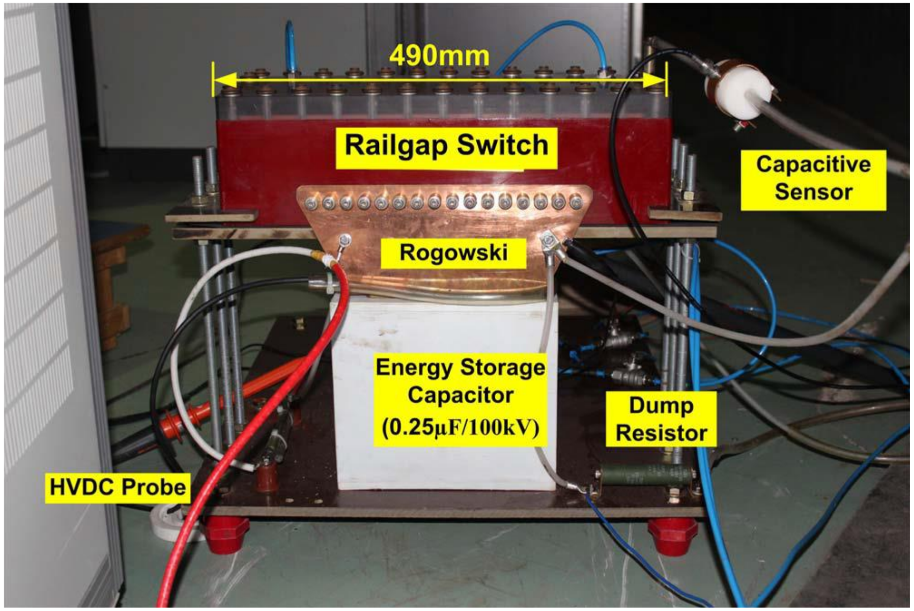


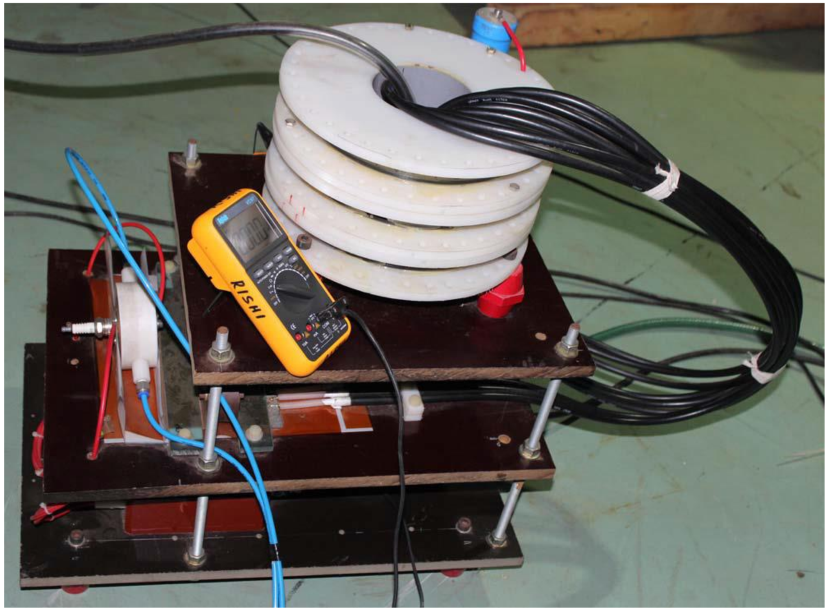
- **Advantages:**
  - **the number of switches is halved.**
  - **The resistances and inductances of the switches have no effect on the circuit output impedance if the LC generator picks up the load through an additional fast switch.**
- **Disadvantage: switches must be operated as simultaneously as possible.**

Adding of voltage pulses by transit-time isolation



Transmission transformer

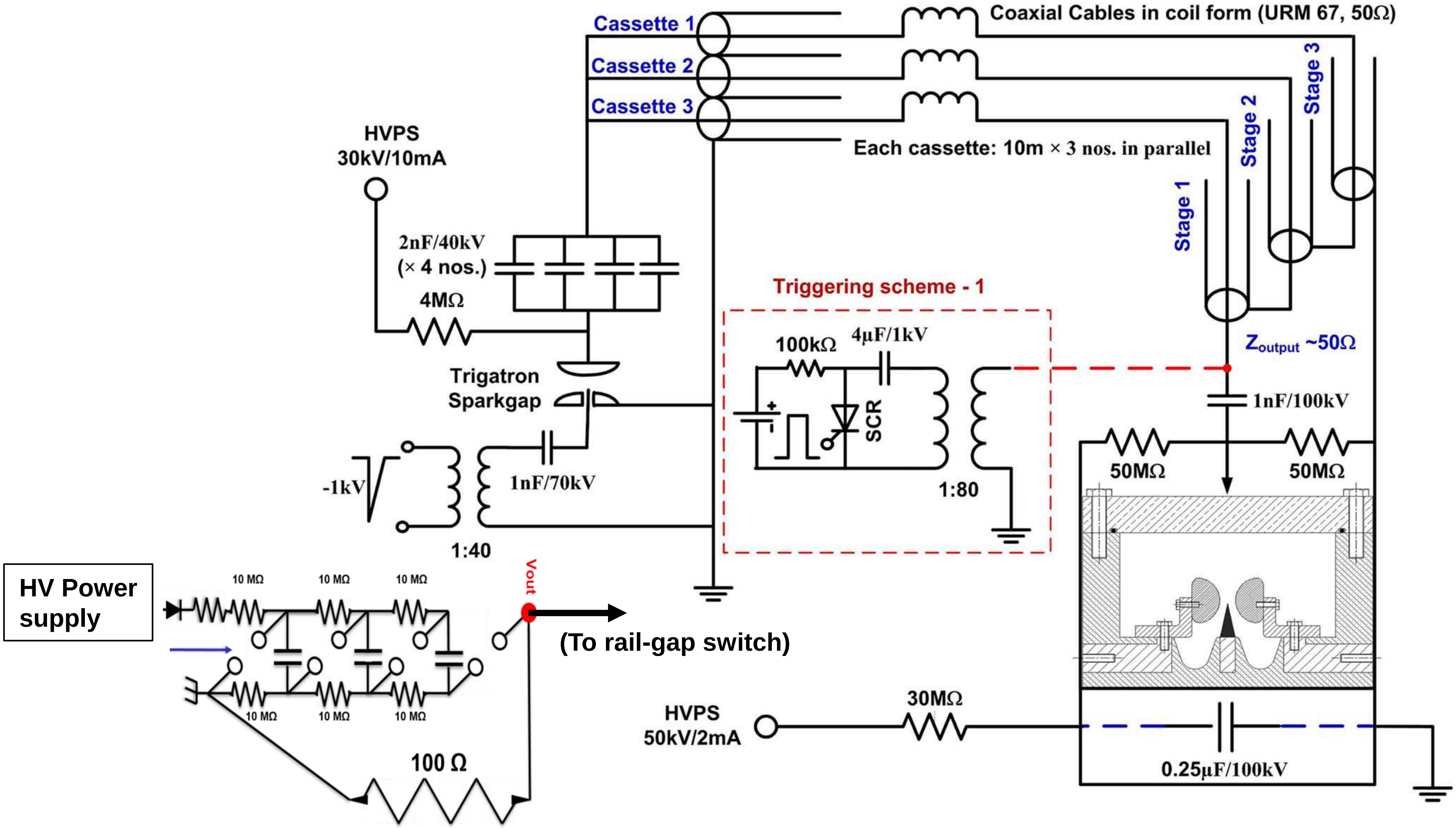




- **Multi-channel discharges between two rail-like electrodes will be triggered by a fast trigger pulse generator (rising speed > 5kV/ns).**

P.-Y. Chang etc. Rev. Sci. Instrum. 91, 114703 (2020)
R.Verma etc., Rev. Sci. Instrum. 85, 095117 (2014)

Transmission transformer



R. Verma, etc., Rev. Sci. Instrum. 85, 095117 (2014)

Line pulse transformers (LTP)

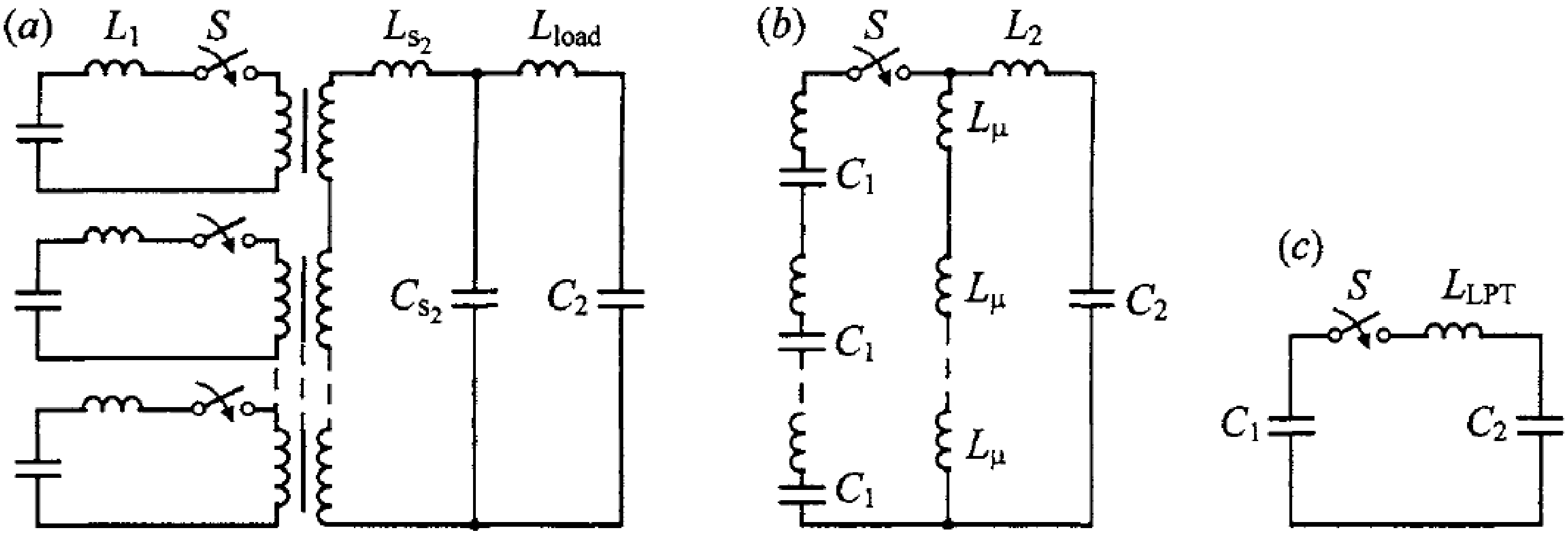
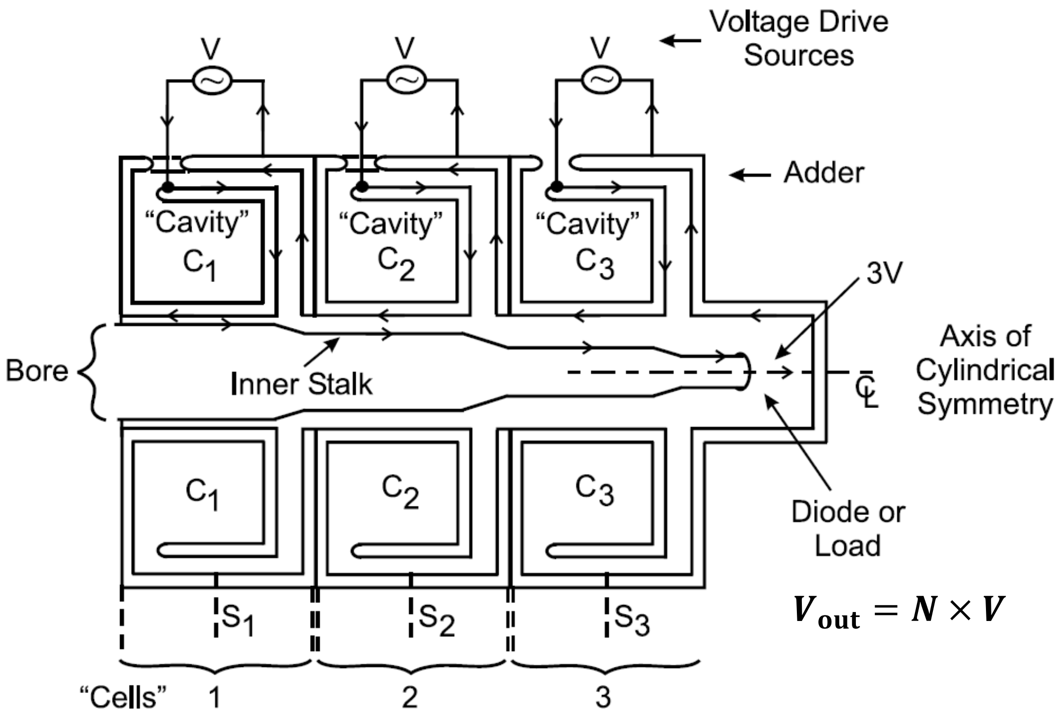


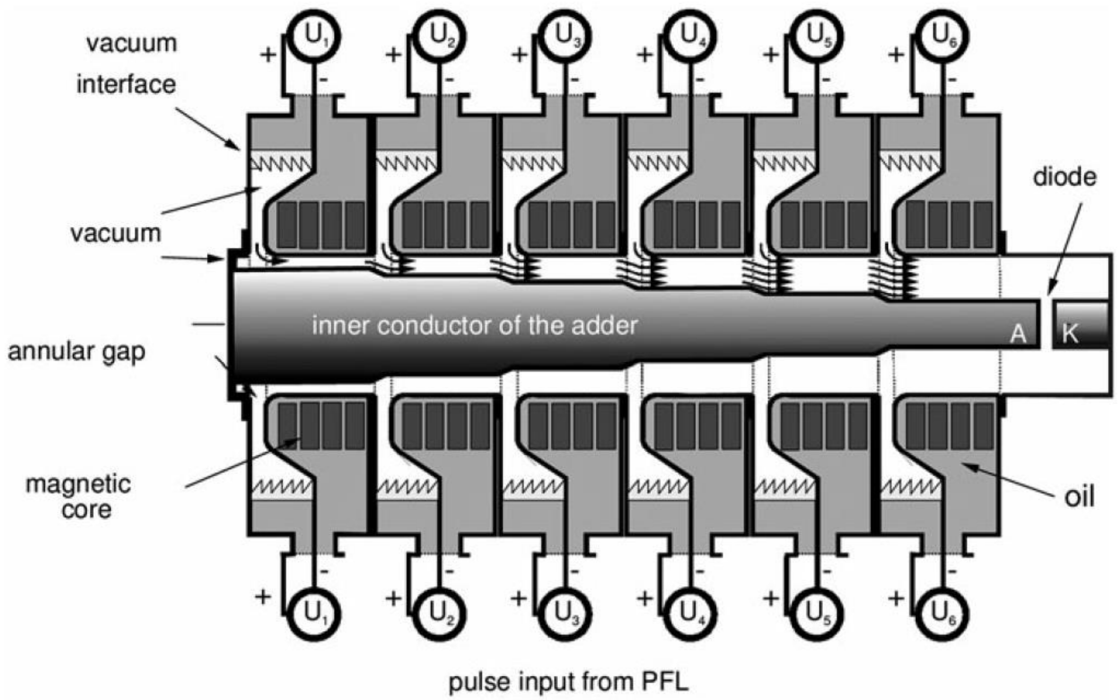
Figure 1.6. The equivalent (a), reduced (b), and simplified circuit (c) of a line transformer

Induction voltage adder (IVA)

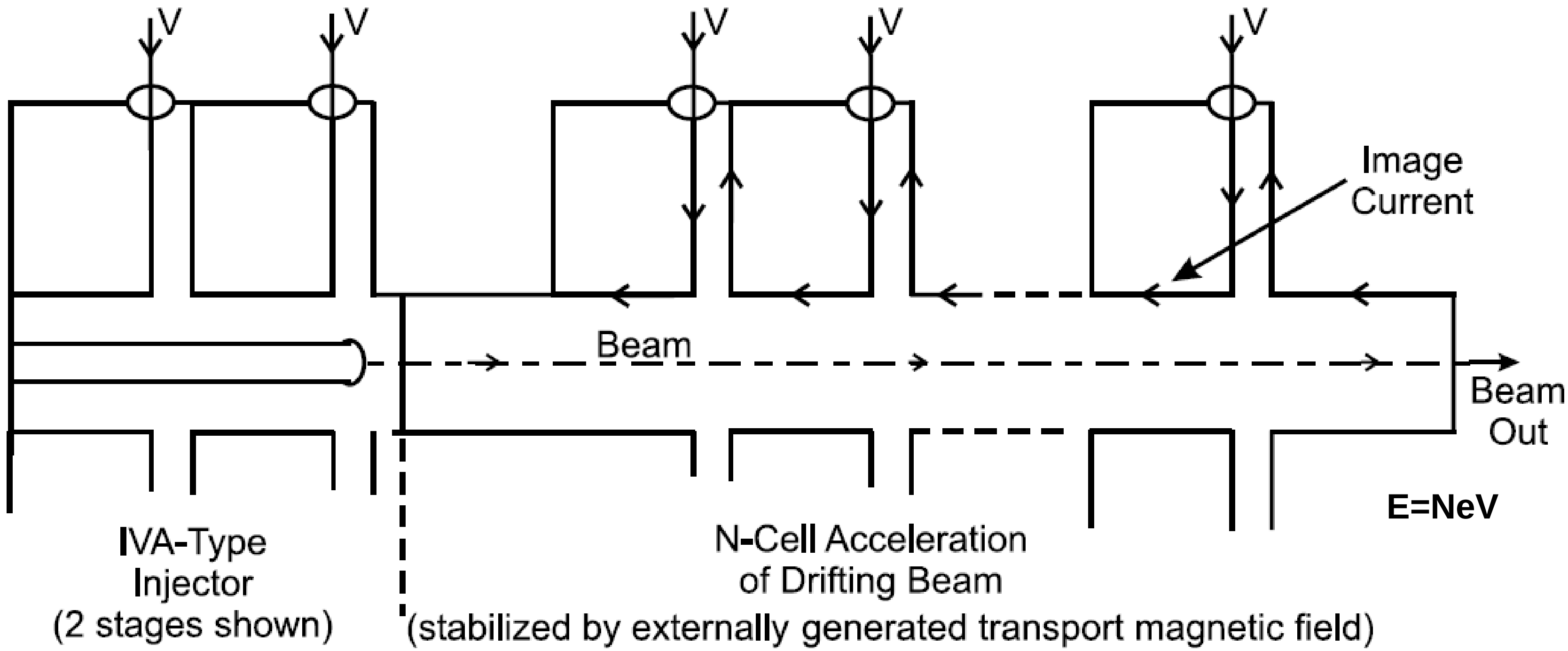


$$V_{\text{out}} = N \times V$$

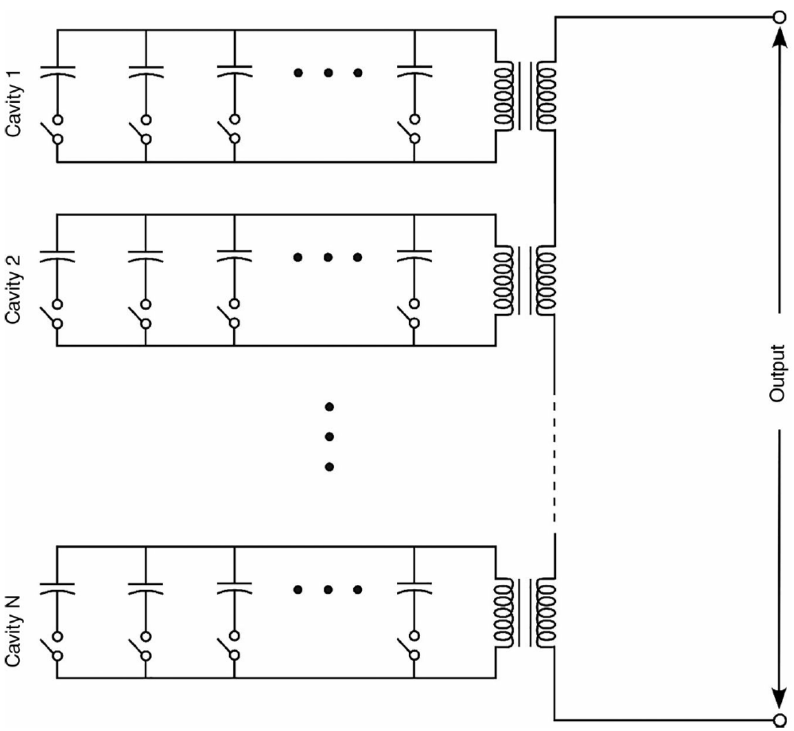
Example of IVA of KALIF-HELIA (High Energy Linear Induction Accelerator)

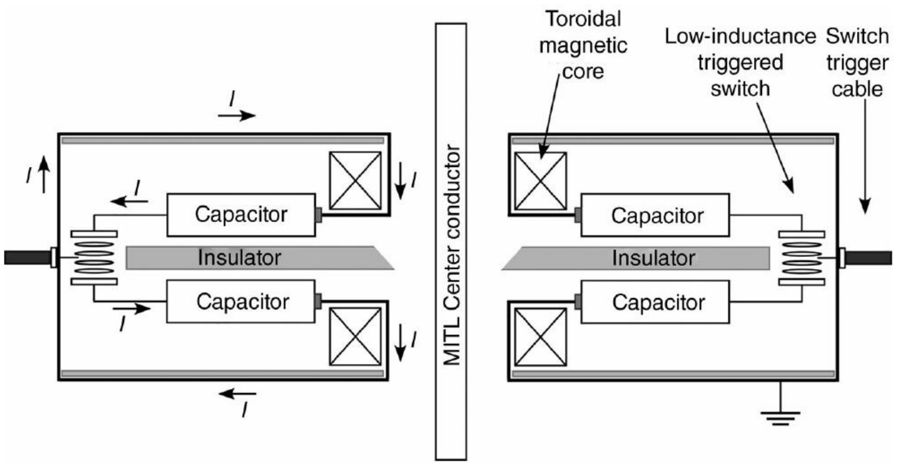


Linear Induction Accelerator (LIA)

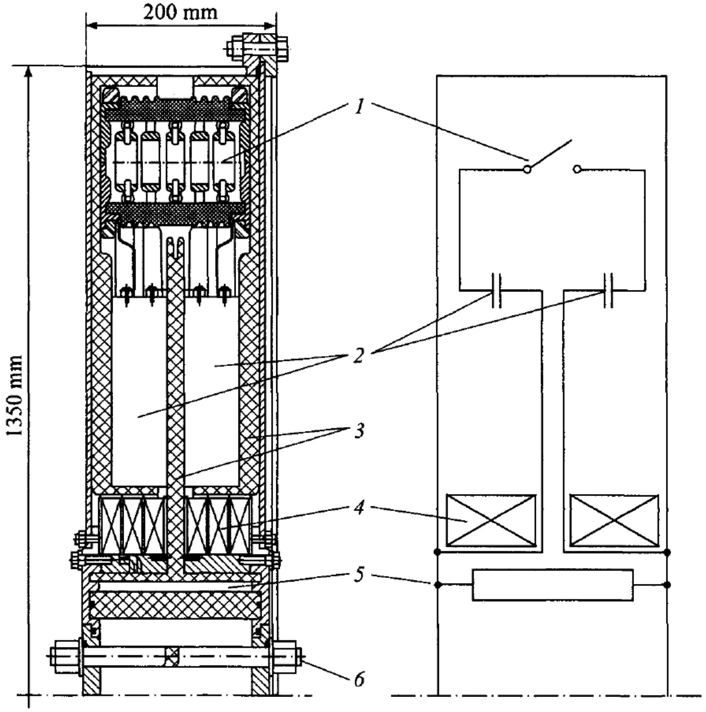


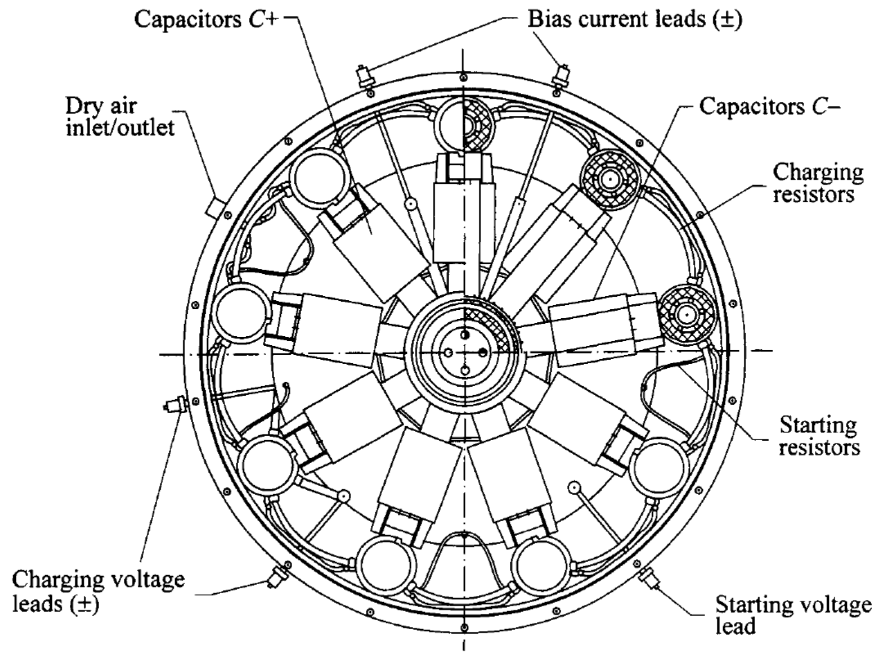
Linear Transformer Driver (LTD)



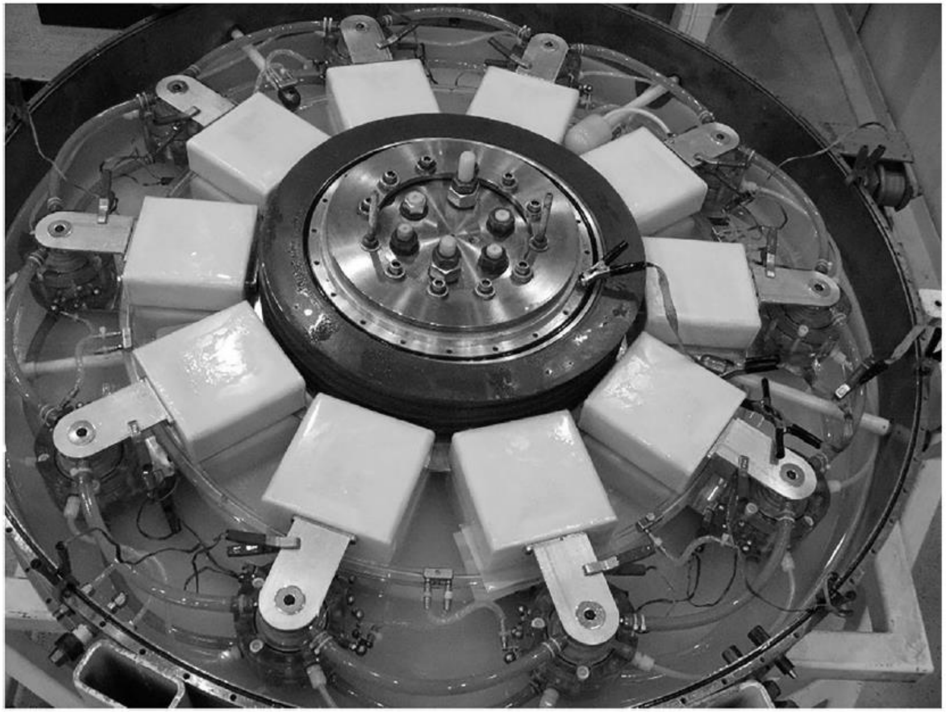


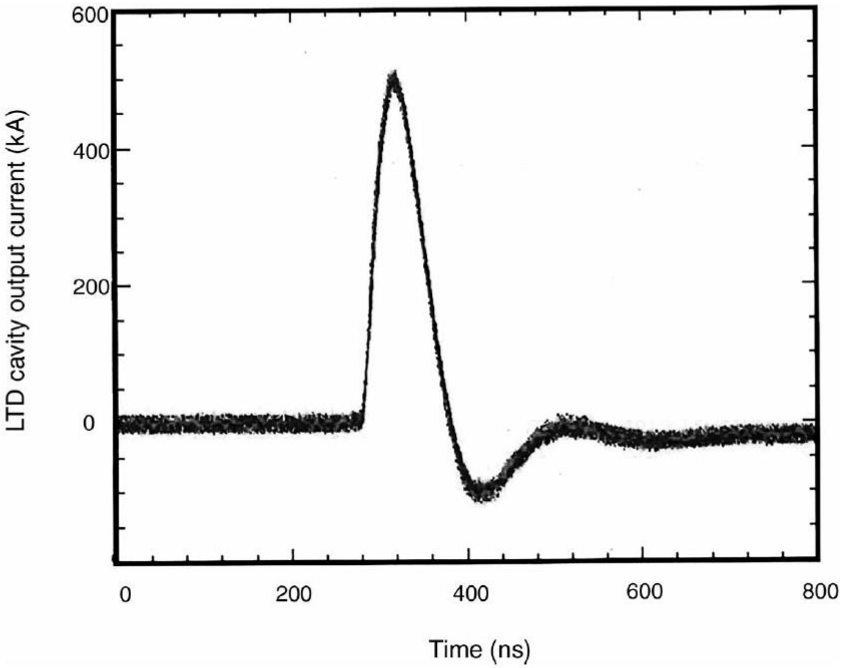
Linear Transformer Driver (LTD)



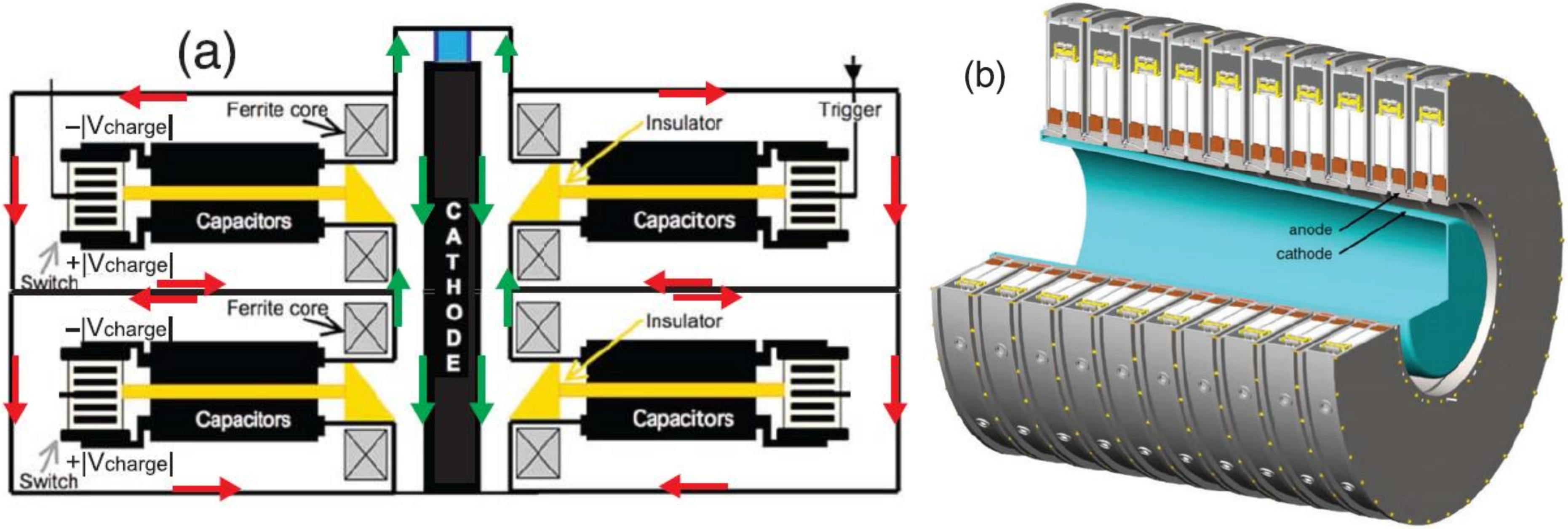


Linear transformer driver





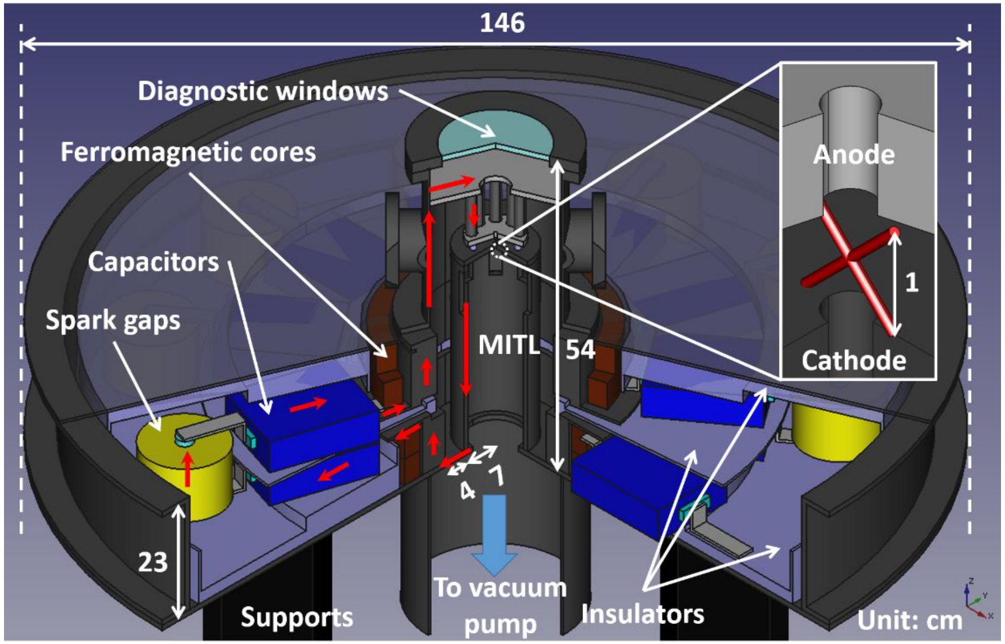
Linear Transformer Driver (LTD)

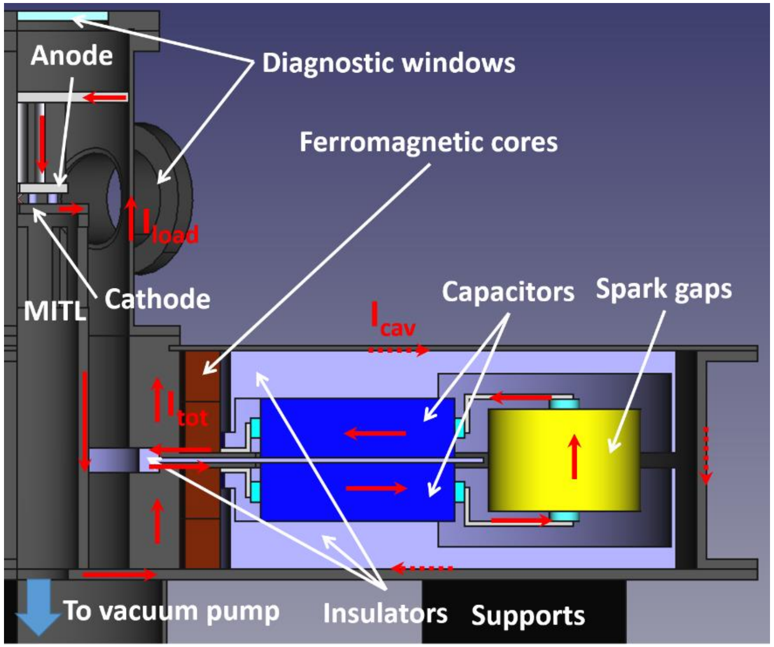


Characteristics of LTD

- **Advantages:**
  - **LTD stages enclose the primary storage. The LTD driver is more compact compared to other generators having similar output parameters.**
  - **LTD driver is simple.**
  - **It is practical and convenient to be built with relatively small size capacitors, which necessarily have less capacitance C. => short pulse**
  - **It can be operated in both LPT and IVA modes.**
- **Small capacitor, and reduced inductance (because of connected in parallel) lead to short pulse width.**
- **To increase energy storage, high voltage is used.**

Our design


146
Diagnostic windows
Ferromagnetic cores
Capacitors
Spark gaps
Anode
1
Cathode
MITL
54
4
7
23
To vacuum pump
Supports
Insulators
Unit: cm


Anode
Diagnostic windows
Ferromagnetic cores
I_{load}
MITL
Cathode
I_{cav}
Capacitors
Spark gaps
I_{tot}
To vacuum pump
Insulators
Supports

Outlines

- Power and voltage adding
  - Marx generator
  - LC generator
  - Line pulse transformers
  - Induction voltage adder (IVA)
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- **Diagnostics**
  - **Voltage measurement**
  - **Current measurement**
- Applications of pulsed-power system

Diagnostics

- **The basic electrical quantities are always the electromagnetic fields E and B from which pulse current and voltage must be derived.**
- **A suitable sensor does not perturb the fields to be measured is achieved with**
  - **capacitive sensors;**
  - **inductive sensors;**
  - **electro-optical methods;**
  - **resistive voltage dividers. It may create weak points in the high-voltage insulation.**

Electromagnetic field sensors

- Rapidly changing electromagnetic fields, i.e., $\frac{d\vec{B}}{dt}$ or $\frac{d\vec{E}}{dt}$

  → induced currents / voltages in the conductors of a sensor.

  → only consider electrically short sensors:

  size < λ of the field where λ is the scale length or wavelength.

  or d << $c\tau_r$, the distance of the wave that propagates where τ_r is the pulse rise time

  → conduction current density: $\vec{j}_c = \sigma\vec{E}$

  displacement current density: $\vec{j}_d = \frac{\partial\vec{D}}{\partial t}$

  Maxwell's eq:

$$\nabla\times\vec{E} = -\frac{\partial\vec{B}}{\partial t}$$

$$\nabla\times\vec{H} = -\frac{\partial\vec{D}}{\partial t} + \vec{j}$$

Electromagnetic field sensors

- **Ideal conducting sensor of area *A*:**

$$i(t) = \left[j_c(t) + \dot{D}(t)\right]A = \left[\sigma E(t) + \epsilon\epsilon_o \dot{E}(t)\right]A$$

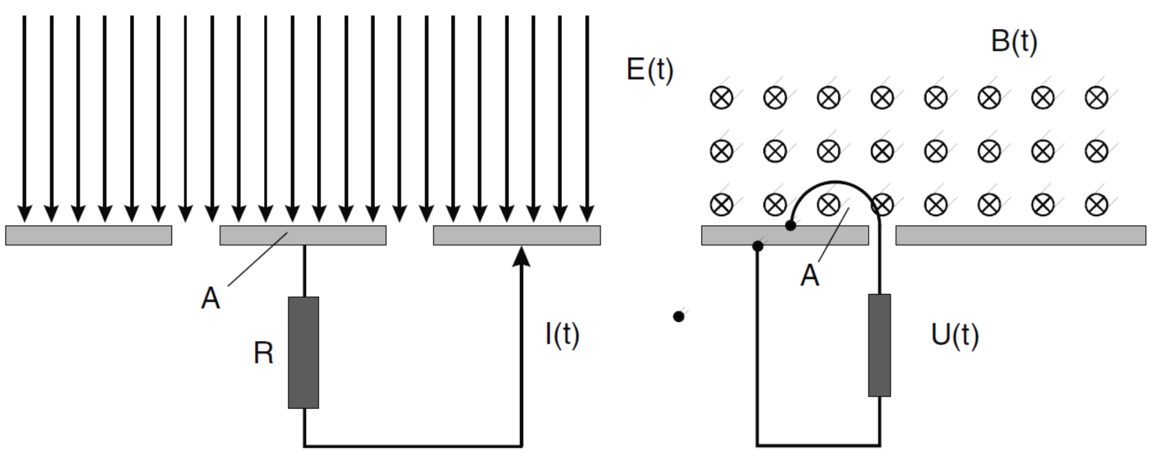
The sensitivity depends on σ, ϵ, *A*, $E(t)$, $\dot{E}(t)$, and ω.

- **Alternating magnetic fields => induce currents in conducting loops.**

$$u(t) = -\oint \dot{\vec{B}}(t)d\vec{A} \approx -\dot{\vec{B}}(t)\vec{A}$$ **<= if field is homogeneous.**

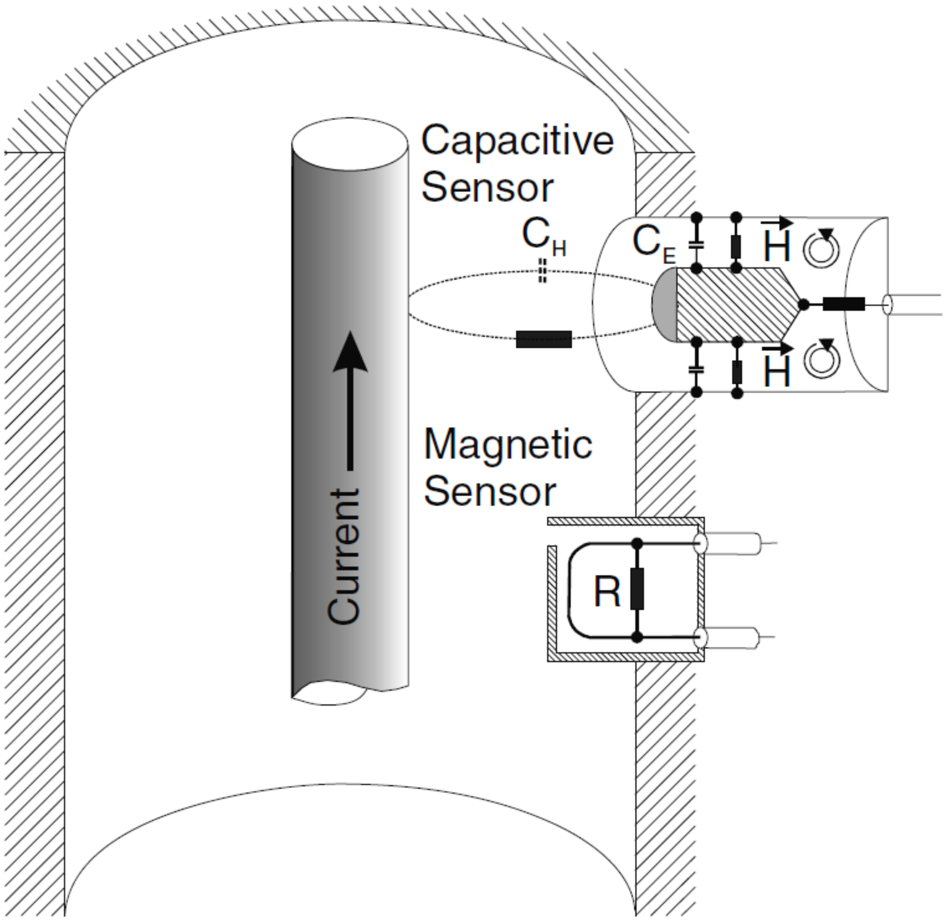
The sensitivity depends on *A*, $\dot{B}(t)$, and ω.

Quasistationary Fields



- **The coupling may also couple the undesired noise.**

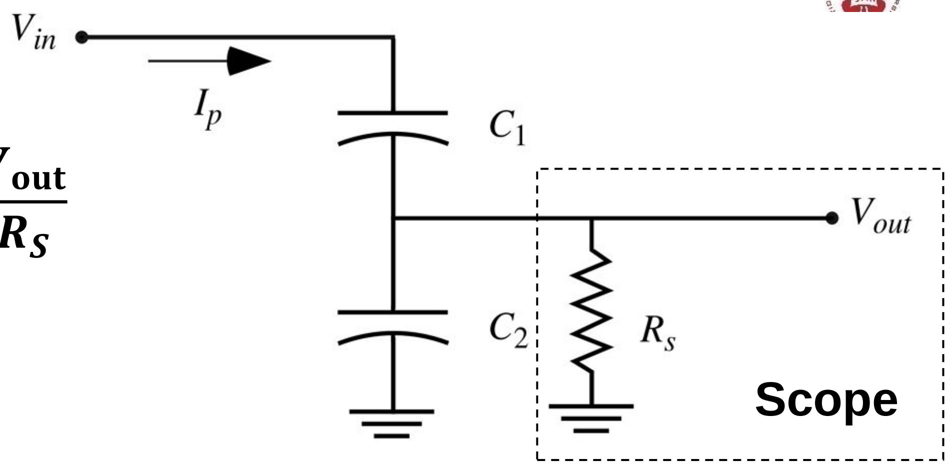
Capacitive/Inductive sensors



$$u(t) = \frac{C_H}{C_H + C_E} U(t)$$

$$u(t) = -\oint \dot{\vec{B}}(t) d\vec{A} = -\frac{d\phi}{dt}$$

Capacitive sensor for voltage measurement



$$V_{\text{in}} = V_{C_1} + V_{\text{out}} \qquad I_p = I_{C_2} + I_{R_s}$$

$$I_p = C_1 \frac{\mathrm{dV}_{C_1}}{\mathrm{dt}} \qquad I_{C_2} = C_2 \frac{\mathrm{dV_{out}}}{\mathrm{dt}} \qquad I_{R_S} = \frac{V_{\text{out}}}{R_S}$$

$$C_1 \frac{\mathrm{dV}_{C_1}}{\mathrm{dt}} = C_2 \frac{\mathrm{dV_{out}}}{\mathrm{dt}} + \frac{V_{\text{out}}}{R_S}$$

$$\frac{dV_{C_1}}{\mathrm{dt}} = \frac{C_2}{C_1} \frac{\mathrm{dV_{out}}}{\mathrm{dt}} + \frac{V_{\text{out}}}{R_S C_1}$$

$$\frac{dV_{\text{in}}}{\mathrm{dt}} = \frac{\mathrm{dV}_{C_1}}{\mathrm{dt}} + \frac{\mathrm{dV_{out}}}{\mathrm{dt}}$$

$$\frac{dV_{\text{in}}}{\mathrm{dt}} = \left(\frac{C_1 + C_2}{C_1}\right) \frac{\mathrm{dV_{out}}}{\mathrm{dt}} + \frac{V_{\text{out}}}{R_S C_1}$$

$$\frac{V_{\text{in}}}{V_{\text{out}}} = \left(\frac{C_1 + C_2}{C_1}\right) + \frac{1}{\mathrm{sR}_S C_1}$$

$$= \left(\frac{C_1 + C_2}{C_1}\right) \left[1 + \frac{1}{\mathrm{sR}_S (C_1 + C_2)}\right]$$

$$\omega_{3\text{dB}} = \frac{1}{R_S (C_1 + C_2)}$$

- **Low frequency:**

$$V_{\text{out}} = \frac{C_1}{C_1 + C_2} V_{\text{in}}$$

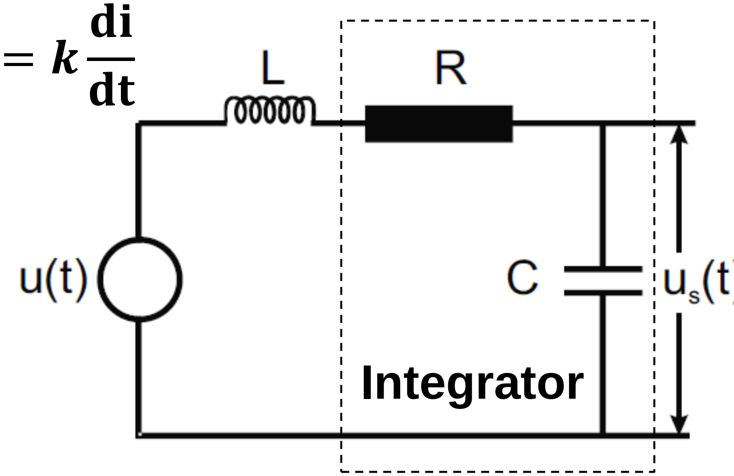
- **High frequency:**

$$V_{\text{out}} = R_S C_1 \frac{\mathrm{dV_{in}}}{\mathrm{dt}}$$

Inductive sensor with RC integrator for current measurement

$$|u(t)| = \frac{d\phi}{dt} = L\frac{di}{dt} + Ri + \frac{1}{C}\int_0^t i\,dt'$$

$$|u(t)| = \frac{d\phi}{dt} = k\frac{di}{dt}$$



$$|u(t)| = \frac{d\phi}{dt} \approx Ri + \frac{1}{C}\int_0^t i\,dt'$$

$$u_s = \frac{1}{C}\int_0^t i\,dt' \Rightarrow C\dot{u}_S = i$$

$$u = RC\dot{u}_S + u_s$$

$$\dot{u}_S + \frac{1}{RC}u_s = \frac{1}{RC}u$$

$$\dot{u}_S e^{\frac{1}{RC}t} + \frac{1}{RC}u_s e^{\frac{1}{RC}t} = \frac{1}{RC}u e^{\frac{1}{RC}t}$$

$$\frac{d}{dt}\left(u_S e^{\frac{1}{RC}t}\right) = \frac{1}{RC}u e^{\frac{1}{RC}t}$$

$$\int d\left(u_S e^{\frac{1}{RC}t'}\right) = \frac{1}{RC}\int_0^t u e^{\frac{1}{RC}t'}dt'$$

$$u_S e^{\frac{1}{RC}t} - u_S(0) = \frac{1}{RC}\int_0^t u e^{\frac{1}{RC}t'}dt'$$

$$u_s = \frac{e^{-\frac{1}{RC}t}}{RC}\int_0^t u e^{\frac{1}{RC}t'}dt' \approx \frac{1}{RC}\int_0^t u\,dt'$$

$$= \frac{k}{RC}i(t)$$

- **Working regime:**

$$RC >> t \approx \frac{1}{\omega} \qquad \omega >> \frac{1}{RC}$$

Rogowski coil

- In situ calibration is needed to obtain *k*.

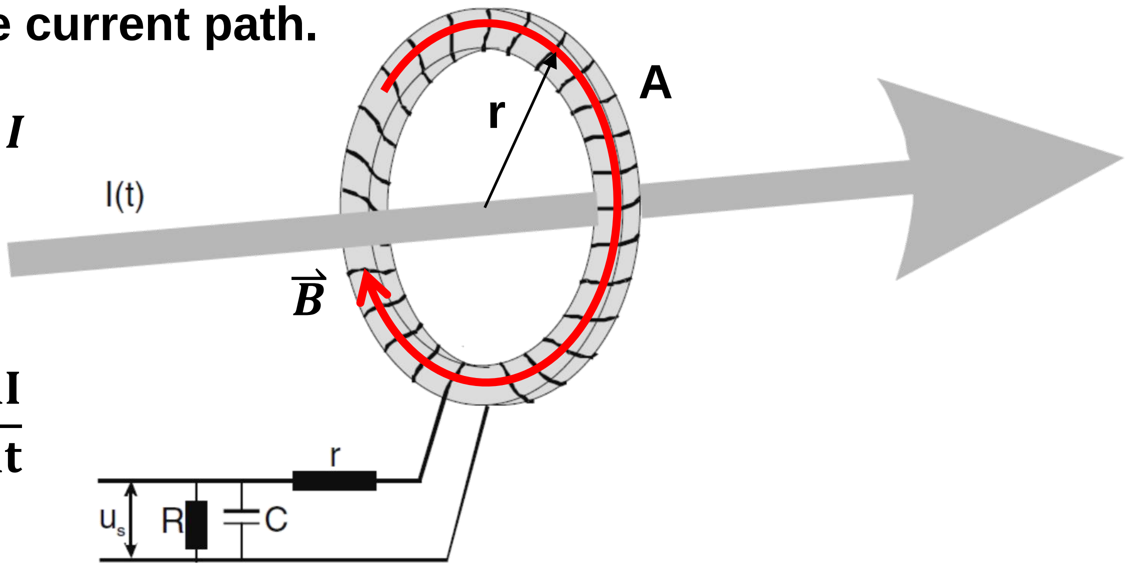
$$|u(t)| = \frac{d\phi}{dt} = k\frac{di}{dt}$$

- If in situ calibration is not possible, Rogowski coil instead of a simple current loop is used.
- Rogowski coil is a coil consisting of many windings lined up in a toroidal configuration encircling the current path.

$$\oint \vec{B} \cdot d\vec{l} = \mu_o I \qquad B = \frac{\mu_o}{2\pi r} I$$

$$\phi_1 = BA = \frac{\mu_o A}{2\pi r} I$$

$$|u| = \frac{d\phi}{dt} = N\frac{d\phi_1}{dt} = \frac{\mu_o AN}{2\pi r}\frac{dI}{dt}$$



$$u_S(t) = \frac{1}{RC}\int u dt = \frac{1}{RC}\frac{\mu_o AN}{2\pi r}\int \frac{dI}{dt} dt = \frac{1}{RC}\frac{\mu_o AN}{2\pi r} I$$

Assumption for Rogowski coil

- Neglect the spatial dependence of the magnetic induction over the area A
- Cross section A are all the same.
- Number of turns per unit length is const.
- When #/ of turns increase,

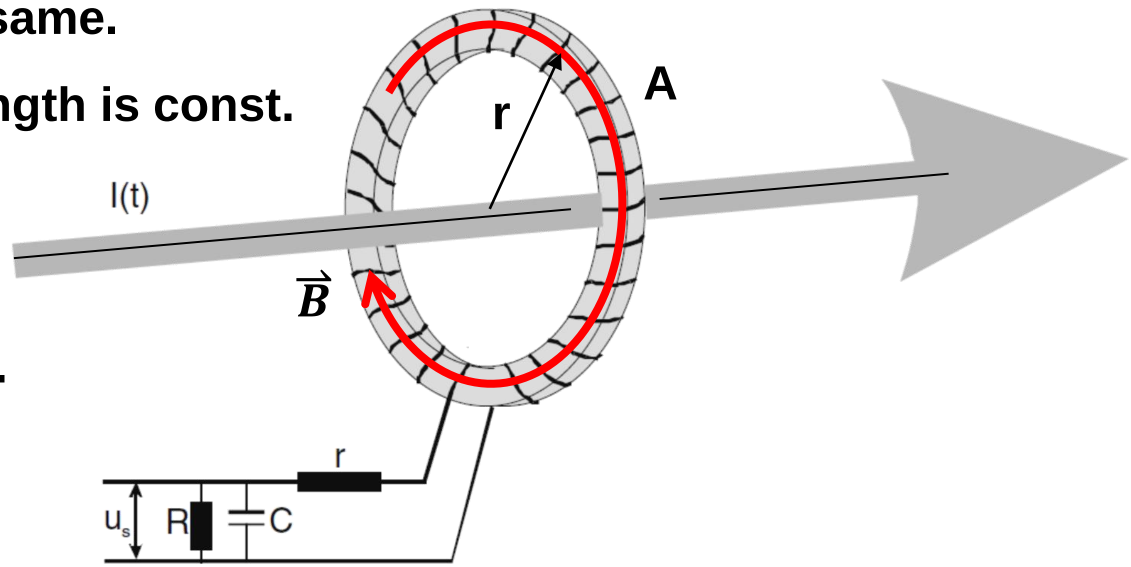
  L may be large

  => Lω << R may not be met.

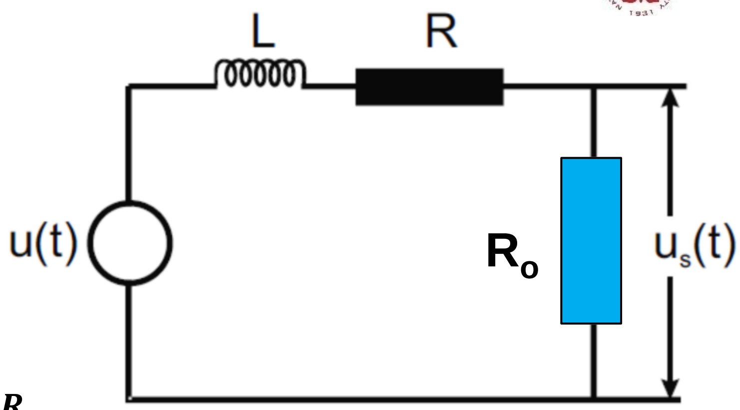
  => use the opposite regime

  where Lω >> R.

  It becomes “self-integrated.”



Self-integrated current monitor where Lω >> R



$R_o >> R \qquad L\omega >> R_o + R$

$$u - L\frac{\mathrm{dI}}{\mathrm{dt}} = u_S \qquad u_S = \mathrm{IR}_o$$

$$u - \frac{L}{R_o}\frac{\mathrm{du_s}}{\mathrm{dt}} = u_S \qquad \frac{du_S}{\mathrm{dt}} + \frac{R_o}{L}u_S = \frac{R_o}{L}u$$

$$e^{-\frac{R_o}{L}t}\frac{d}{\mathrm{dt}}\left(u_s e^{\frac{R_o}{L}t}\right) = \frac{R_o}{L}u \qquad \frac{d}{\mathrm{dt}}\left(u_s e^{\frac{R_o}{L}t}\right) = \frac{R_o}{L}\mathrm{u}e^{\frac{R_o}{L}t}$$

$$u_S e^{\frac{R_o}{L}t} - u_S(0) = \frac{R_o}{L}\int \mathrm{u}e^{\frac{R_o}{L}t'}\mathrm{dt}'$$

$$u_s = \frac{R_o}{L}e^{-\frac{R_o}{L}t}\int \mathrm{u}e^{\frac{R_o}{L}t'}\mathrm{dt}' \qquad \mathrm{L}\omega >> R_o \qquad t\frac{R_o}{L} \ll 1 \quad |u| = \frac{\mathrm{d}\phi}{\mathrm{dt}} = N\frac{\mathrm{d}\phi_1}{\mathrm{dt}} = \frac{\mu_o \mathrm{AN}}{2\pi\mathrm{r}}\frac{\mathrm{dI}}{\mathrm{dt}}$$

$$u_s = \frac{R_o}{L}\int \mathrm{udt}' = \frac{R_o}{L}\int \frac{\mu_o \mathrm{AN}}{2\pi\mathrm{r}}\frac{\mathrm{dI}}{\mathrm{dt}}\mathrm{dt}' = \frac{R_o}{L}\frac{\mu_o \mathrm{AN}}{2\pi\mathrm{r}}I$$

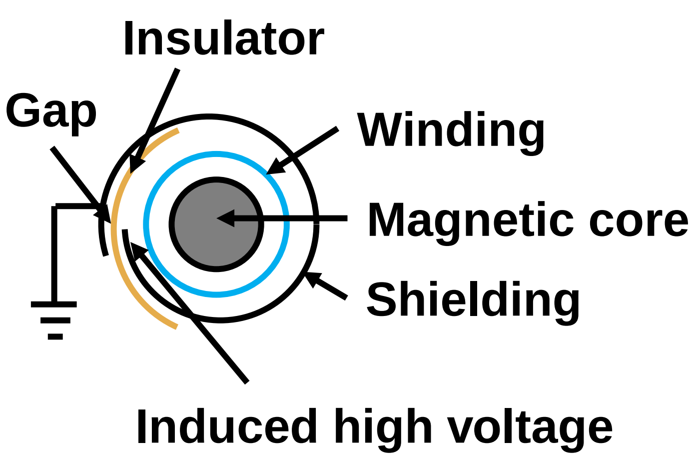
<= self integrated!

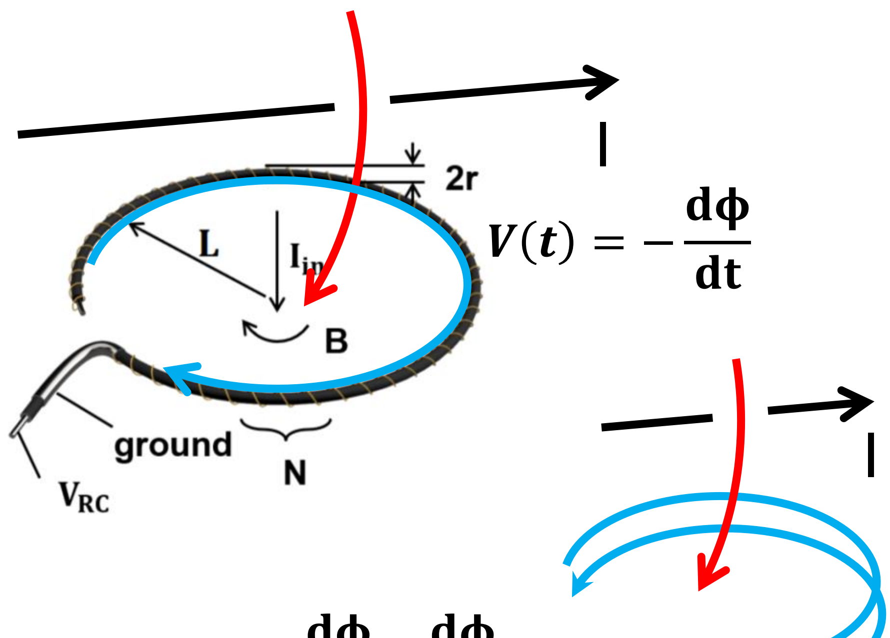
$u_S \propto R_o$

- **Ferromagnetic material in the torus may be used to increase inductance.**

Additional note for Rogowski coil

- **To reduce the capacitive coupling, wrap the Rogowski coil with a slotted metallic case. However, it need to let the flux goes into the winding. NO closed loop is allowed.**
- **A large flux penetrating the main opening of the torus may induce additional voltage. To compensate for this signal, feed one end of the wire back through the windings**



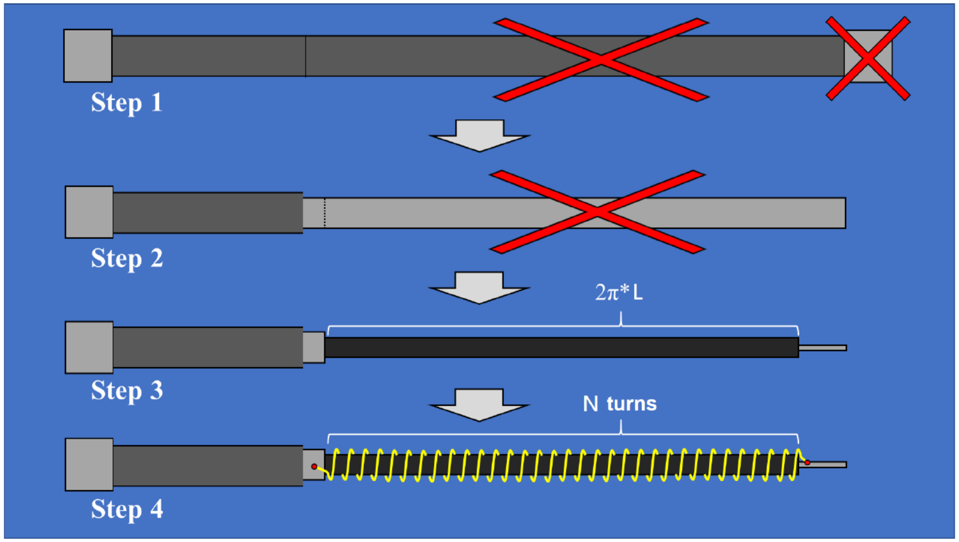


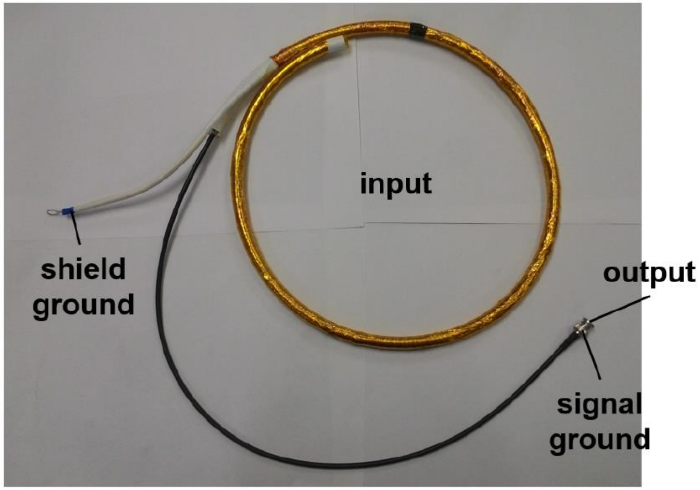
$$V(t) = -\frac{d\phi}{dt}$$

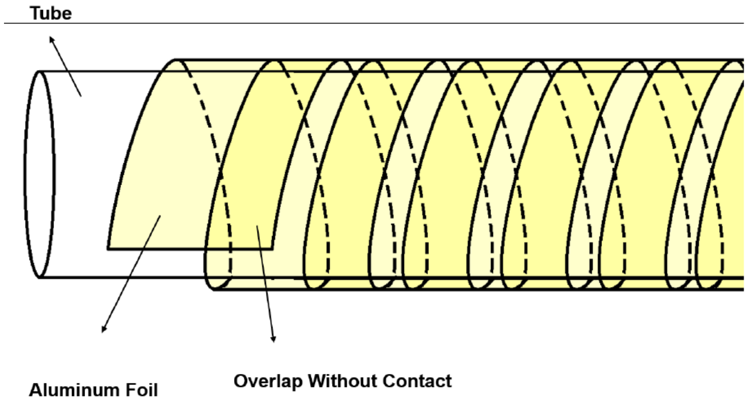
$$V(t) = -\frac{d\phi}{dt} + \frac{d\phi}{dt} = 0$$

Chih-Rui Hsieh, Master thesis (2020)

Fabrication of the Rogowski coil using a coaxial cable



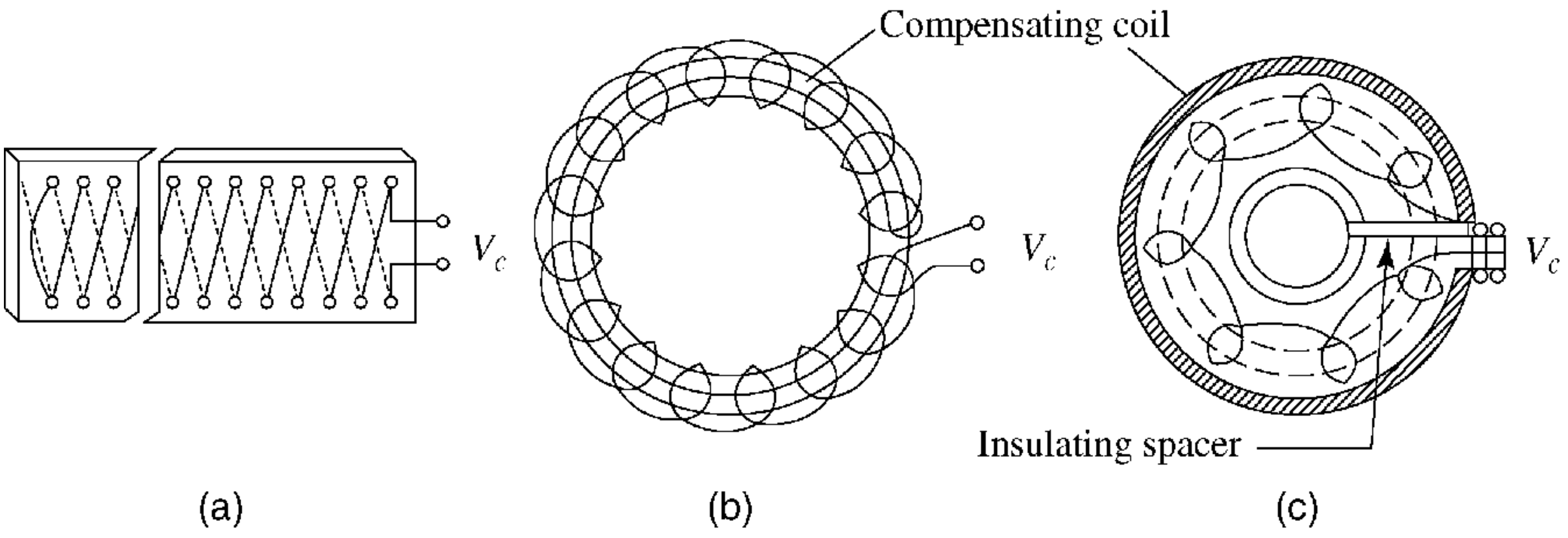




Chih-Rui Hsieh, Master thesis (2020)

Other ways of making compensated Rogowski coil

- **Bifiliar**
- **Inner compensating coil**
- **Outer compensating coil**



Current-viewing resistors (CVRs)

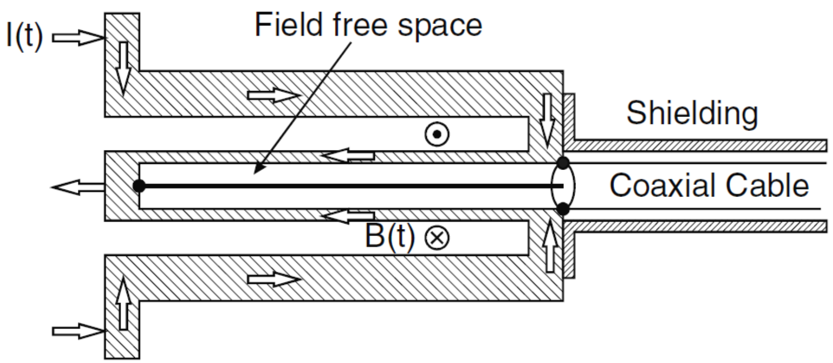
- **It is also called “shunts.”**
- **Measurement of the voltage drop across a resistor of known value, incorporated into the circuit.**

$$I = \frac{V}{R}$$

- **The current path and the measuring circuit are coupled not only through the Ohmic resistor but also magnetically.**

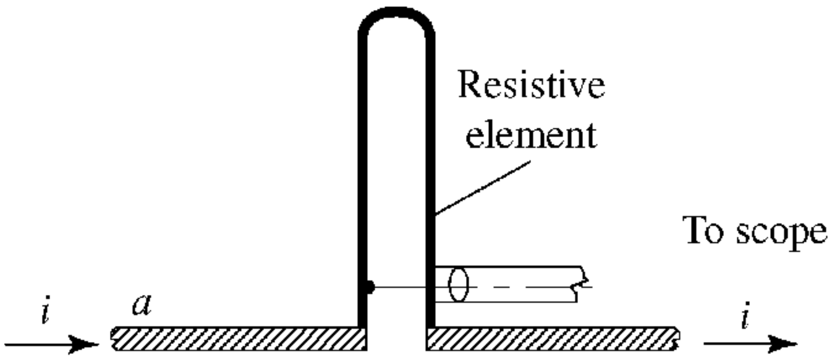
=> preferable to place the metering contact in a field-free space or reduce the coupling efficiency.

- **Cylindrically symmetric shunt geometry provides an zero magnetic coupling.**



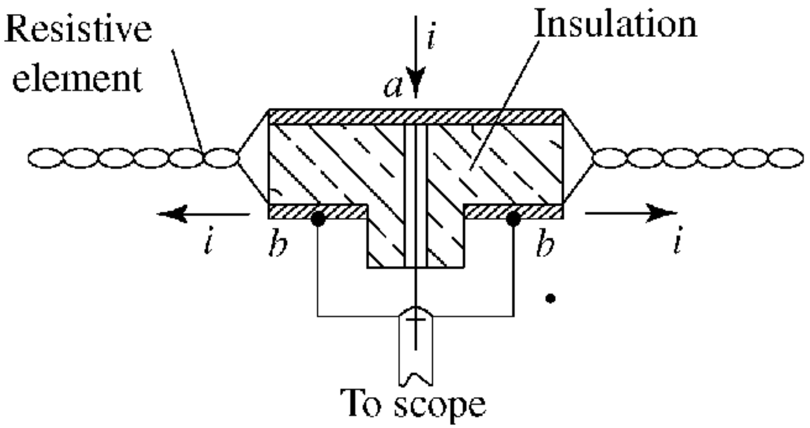
Shunts

- Folded strip shunt



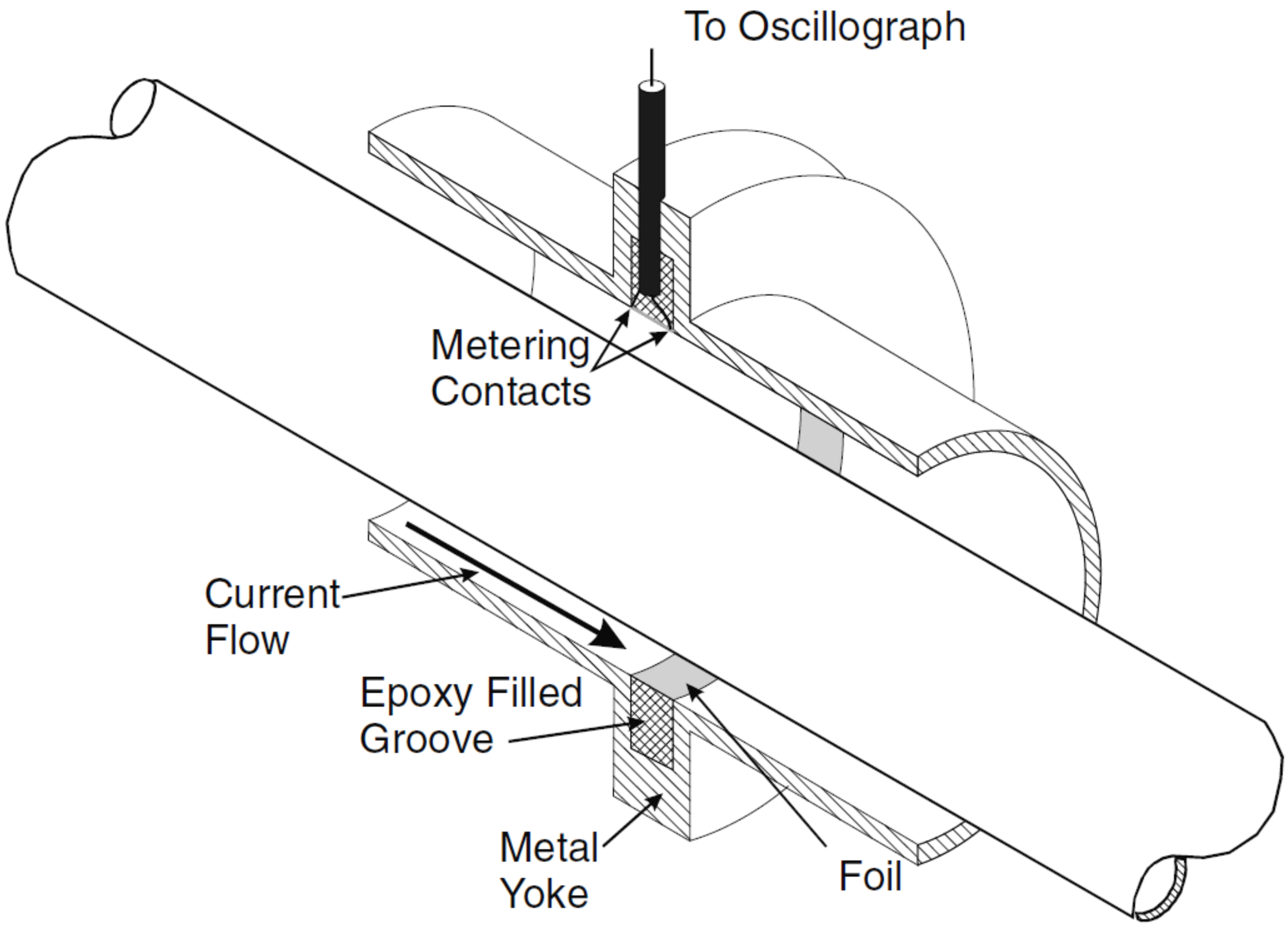
(a)

- Parallel twisted shunt

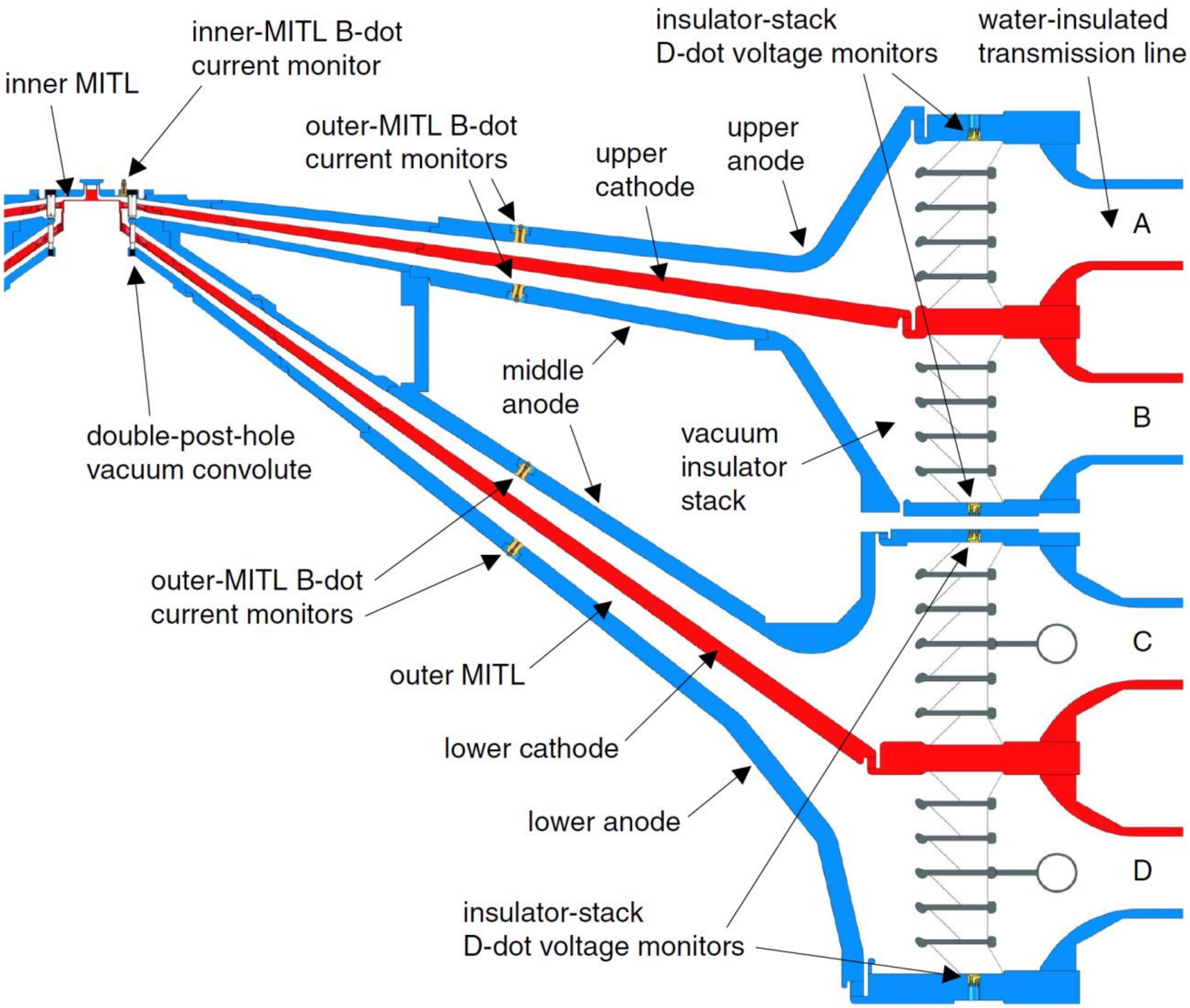


(b)

CVR integrated into the outer conductor of a coaxial transmission line



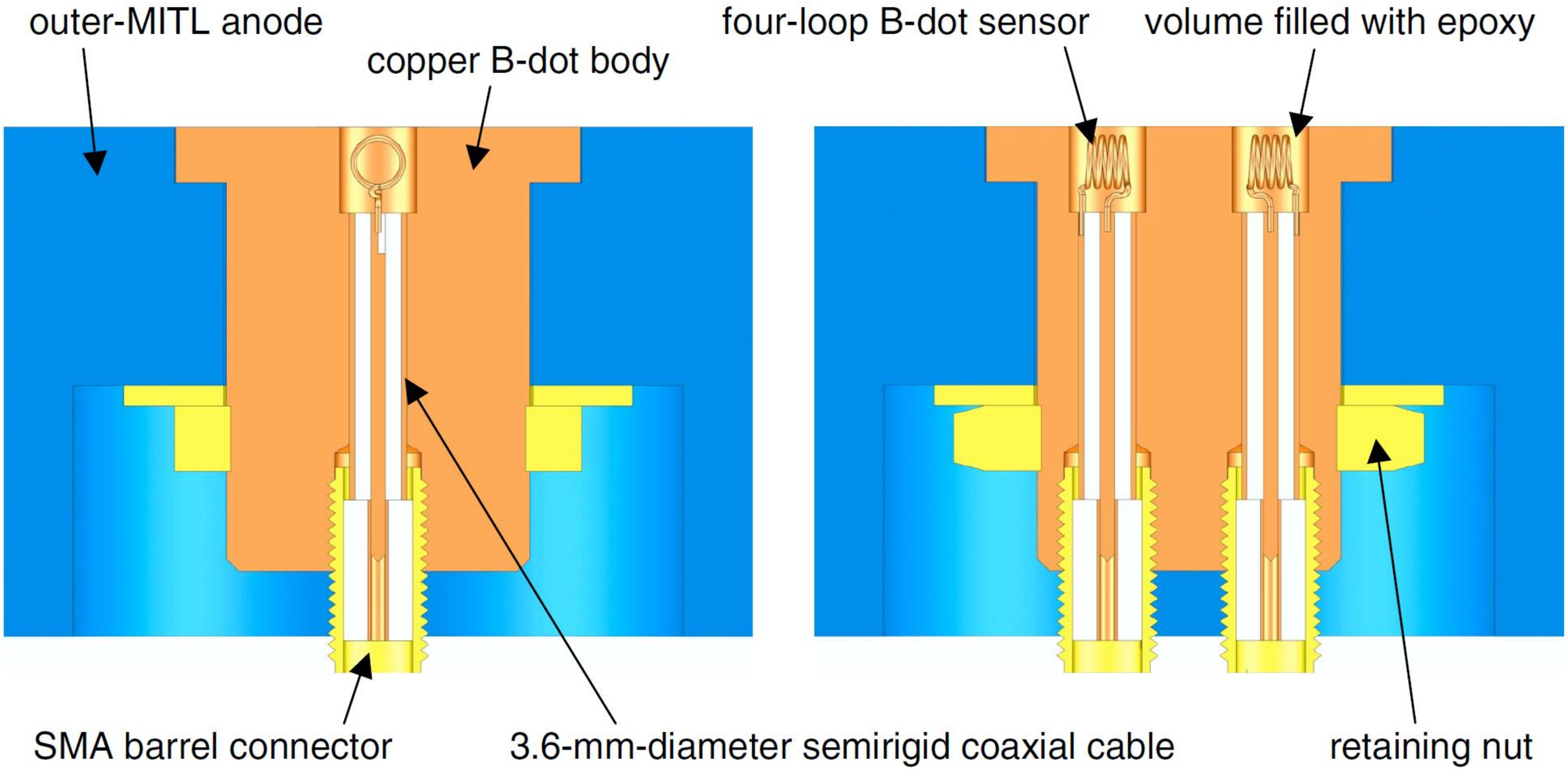
Example of current and voltage monitor using B-dot and D-dot monitors



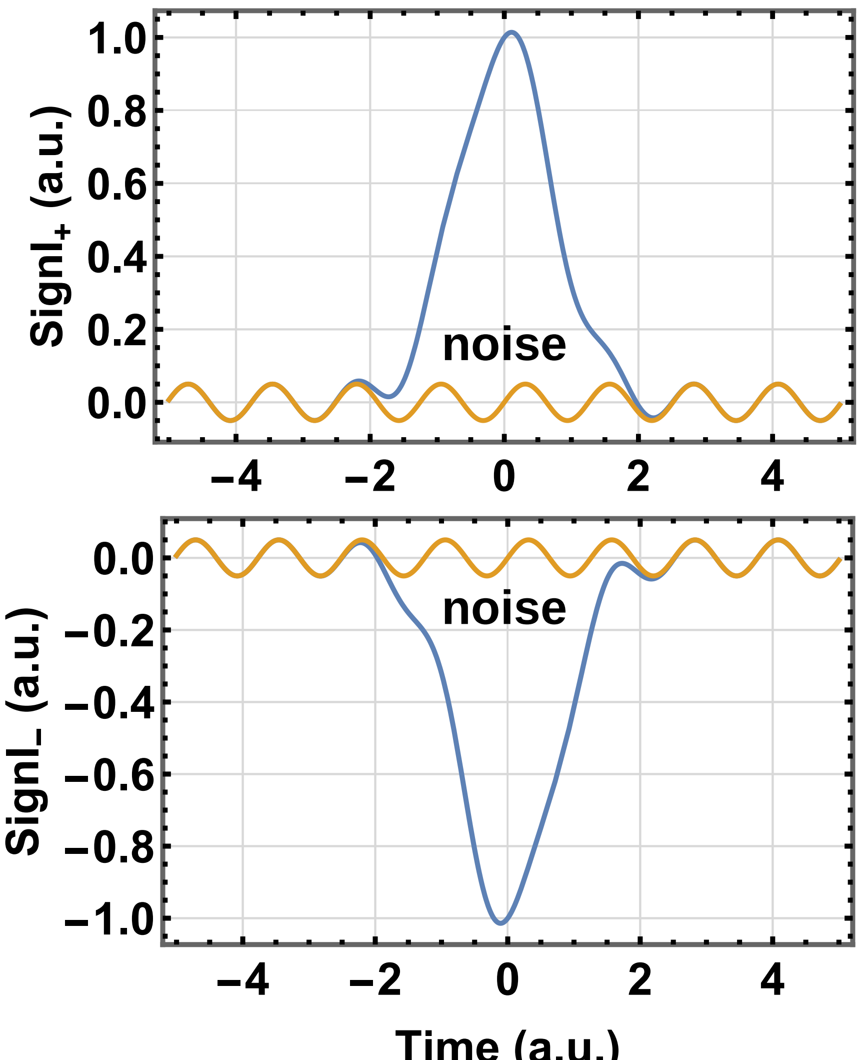
T. C. Wagoner, etc., Phys. Rev. ST Accel. Beams 11, 100401 (2008)

Differential current monitors

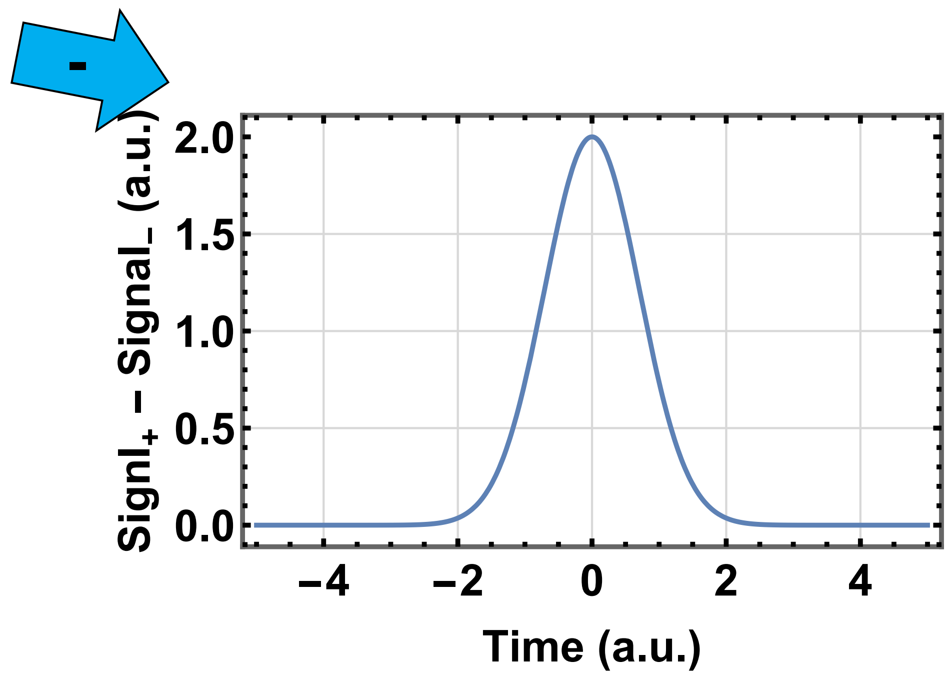
- **Outer MITL B-dot current monitors:**



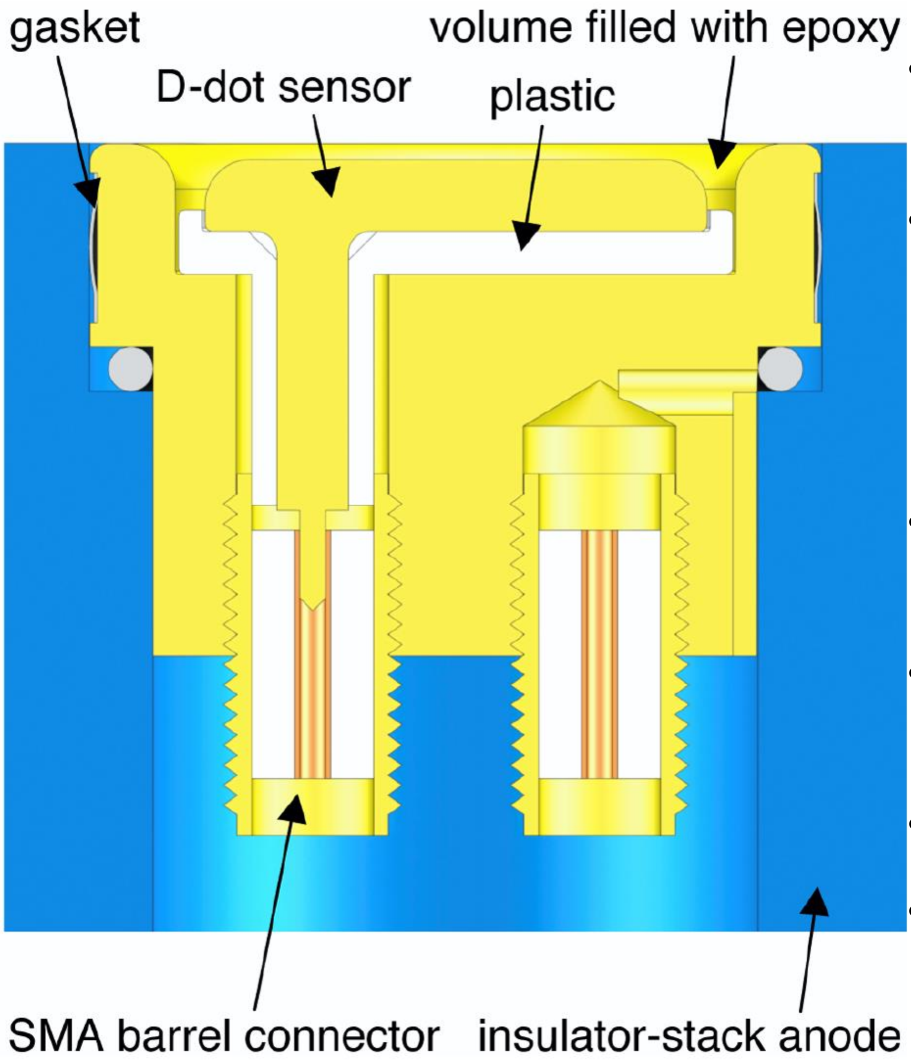
Differential current monitors



- The two B-dot sensors of each B-dot current monitor are designed to produce “opposite-polarity” signals for “common-mode-noise” rejection.



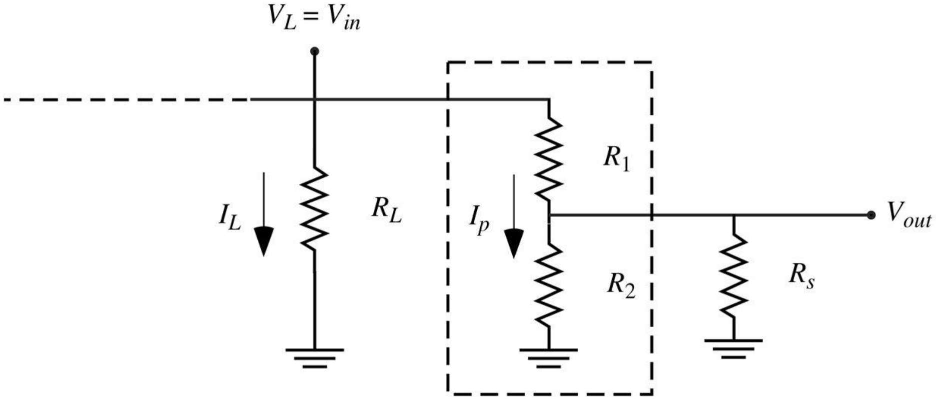
Differential voltage monitor

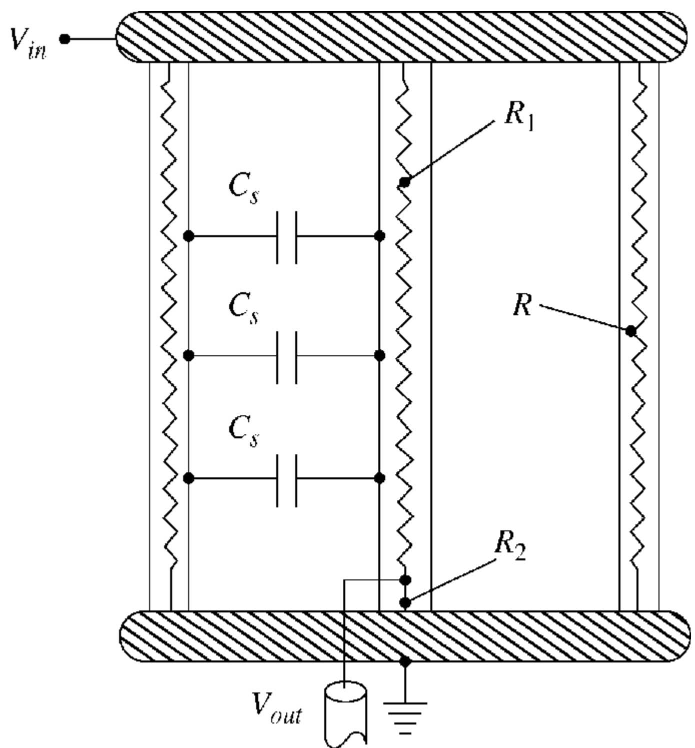


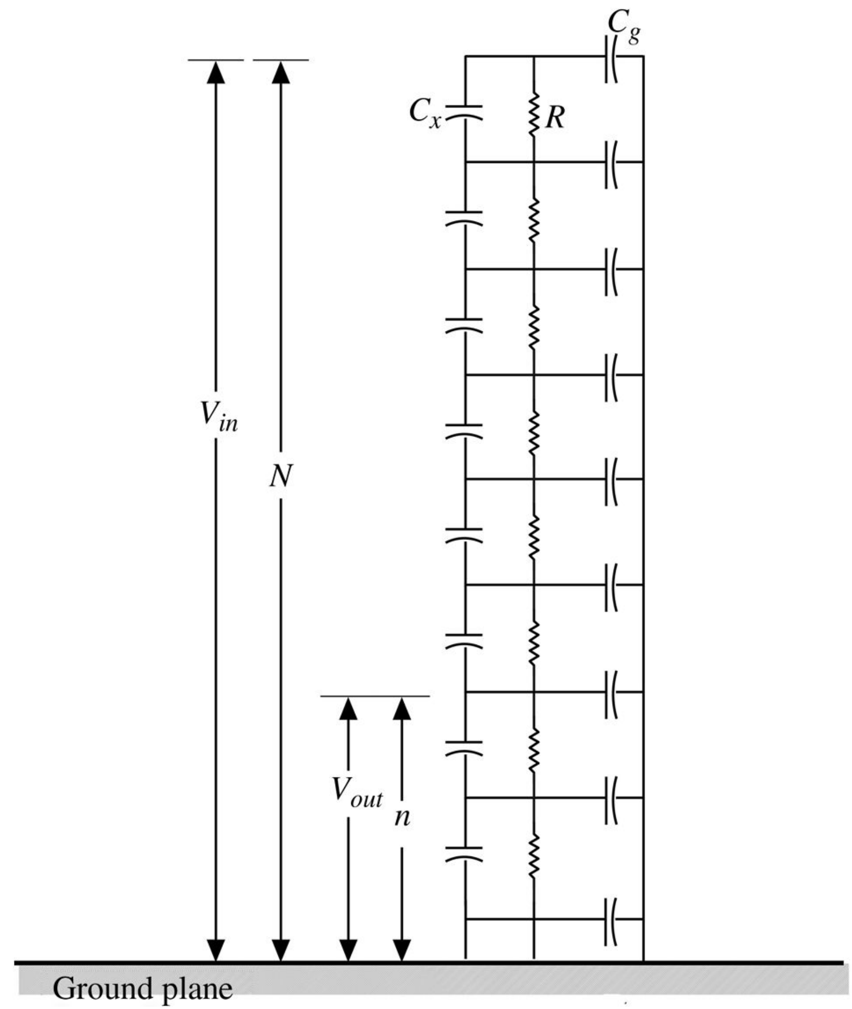
- D-dot voltage monitor: the displacement-current monitor
- Opening-circuit termination for null measurements, i.e., common-mode noise reduction.

- Vacuum potted using stycast epoxy.
- Common-mode noise reduction is applied.
- Numerically cable compensated.
- Numerically integrated the signal.

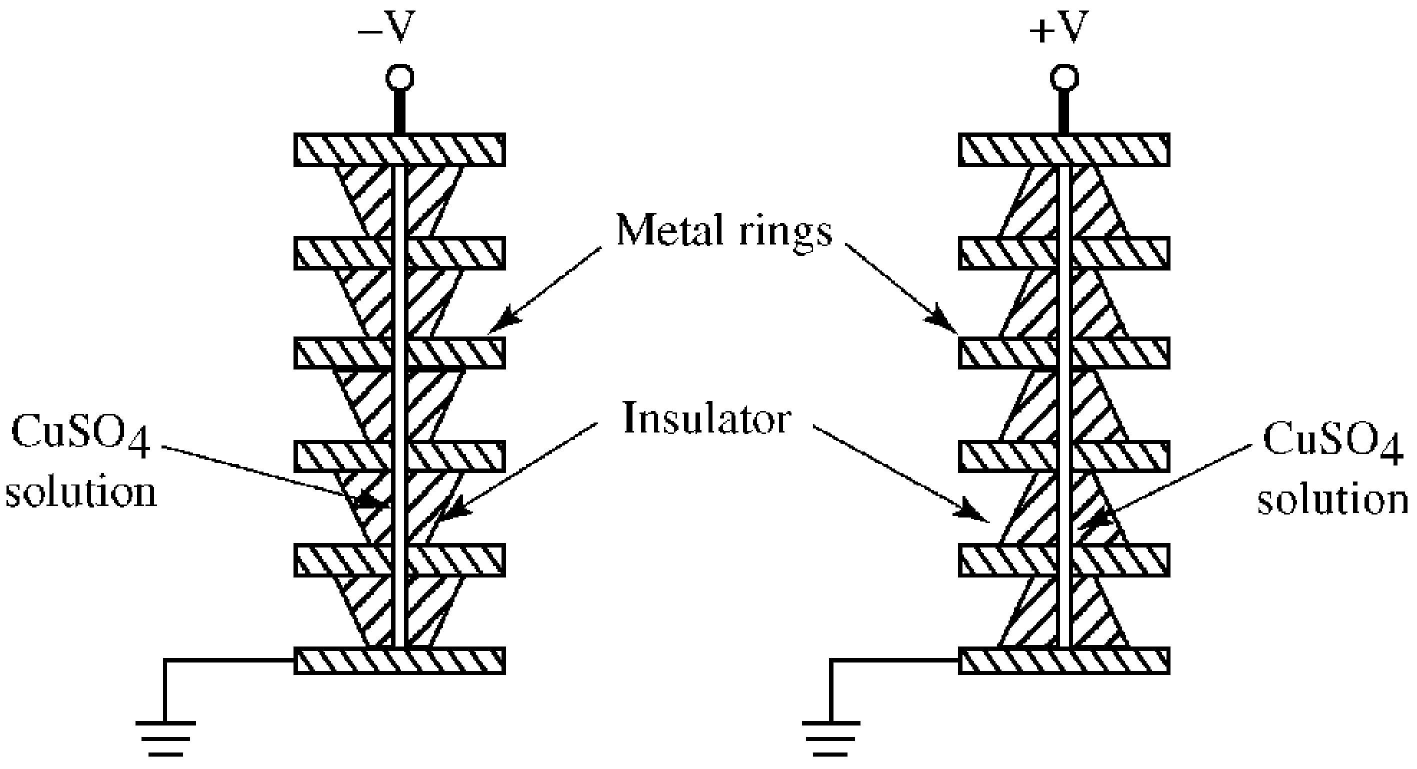
Voltage divider using resistors



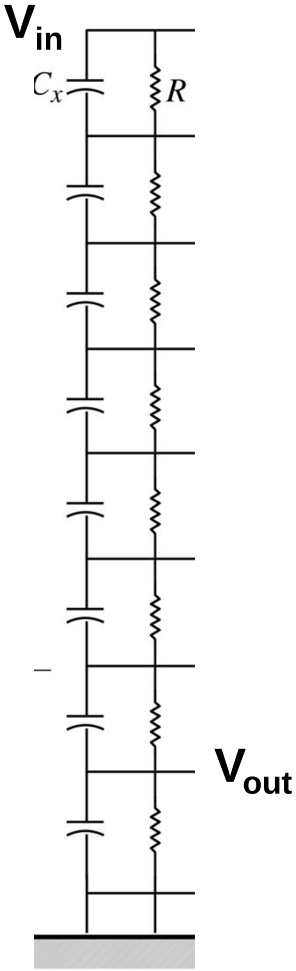




Voltage divider liquid resistors and grading electrodes



Voltage divider using both resistors and capacitors



- **Low frequency:**

$$V_{\text{out}} = \frac{R_o}{\Sigma R_o} V_{\text{in}} = \frac{R_o}{N R_o} V_{\text{in}} = \frac{1}{N} V_{\text{in}}$$

- **High frequency:**

$$V_{\text{out}} = \frac{\frac{1}{j\omega C_o}}{\Sigma \frac{1}{j\omega C_o}} V_{\text{in}} = \frac{\frac{1}{j\omega C_o}}{N \frac{1}{j\omega C_o}} V_{\text{in}} = \frac{1}{N} V_{\text{in}}$$